

A Value Approach To Complex System Design Utilising A Non-Rigid Solution Space

A thesis submitted for the Degree of Doctor of Philosophy

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Abstract

The research presented in this thesis develops an improved design methodology for developing complex systems. While traditional methods have been able to create complex systems, their success is usually overshadowed by long delays and expensive overruns. The method developed within this research is known as Value Seeking System Design (VSSD) and builds upon the foundations of the System Engineering and Value Driven Design approaches. Creation and implementation of the new design environment is provided, including a method on how to create the value model.

Key conclusions from this work include a need to redefine the process in which stakeholder needs are currently defined and captured as well as a need to create an improved value model. Defining all stakeholders' needs as requirements constrains the designer to a rigid solution space, which may not include the "best" solution for the stakeholder. Similarly not including the social aspects within a value model causes the designer to make poor value trades. To overcome these problems the VSSD technique incorporates desirability functions and their associated design desirability functions within the design process to create a non-rigid solution space while the value model has been redeveloped to easily incorporate the performance, economic and social aspects of a design, to allow a more accurate and balanced value trade off analysis to occur.

To benchmark the VSSD approach against the current state of the art methods, a simplified design problem was generated i.e. the development of a new commercial aircraft, along with a comprehensive value model. The model linked a state of the art physics-based aircraft synthesis code with an enhanced life cycle assessment algorithm. The combined model was then further enhanced to incorporate existing value models as well as novel value models proposed in the current research. While each approach selected a different

design concept as the “best” solution, the results of the value techniques returned somewhat similar conclusions highlighting the advantages of adapting a value approach to complex system design compared to traditional requirement based techniques. The VSSD approach however was the superior method of the value approaches because of its ability to more accurately capture social aspects within its value model. Therefore, the VSSD method is seen as an improvement over the VDD and SE approach, and is preferred.

In summary the Value Seeking System Design approach is an improved design process capable of developing complex system as it retains the benefits inherent within the System Engineering and Value Driven Design approaches without suffering from their limitations.

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“Not everything that can be counted counts and not everything that counts can be counted”

Albert Einstein

Table of Contents

Abstract	i
Acknowledgments	iii
List of Figures	viii
List of Tables	x
Nomenclature	xii
Chapter 1: Introduction and Motivation	1
1.1 The Engineering Design Process.....	1
1.2 What Is A System?.....	2
1.2.1 The Trend Of Growing System Complexity	2
1.2.2 System Complexity	3
1.2.3 Problems Associated With Growing System Complexity	5
1.3 Development Of Complex Systems.....	5
1.3.1 System Engineering (SE)	6
1.3.1.1 An Introduction To The System Engineering Process	6
1.3.1.2 The System Engineering Process.....	7
1.3.1.3 Advantages And Limitations Of The System Engineering Approach.....	12
1.3.1.4 Complexity theory.....	17
1.3.2 Value Driven Design (VDD).....	18
1.3.2.1 Value	18
1.3.2.2 An Introduction To The Value Driven Design Process	20
1.3.2.3 Value Driven Design Process.....	22
1.3.2.4 Advantages And Limitations Of The Value Driven Design Approach.....	24
1.3.3 A Comparison Between The SE And VDD Techniques.....	29
1.4 Summary	32
Chapter 2: Research Questions, Hypothesis and Thesis Synopsis	33
2.1 Research Questions And Hypothesis	33
2.2 Thesis Synopsis.....	35
Chapter 3: Evolution Of Design Framework	38
3.1 A Brief Review Of The SE And VDD Limitations.....	39
3.2 The Role Of Requirements Within The Design Process	41
3.2.1 Requirements	41
3.2.2 Fuzzy Logic.....	47

3.2.3	Capturing Stakeholder Need Within New Design Process	51
3.3	The Role Of An Objective Function Within The Design Process	57
3.3.1	Objective Function Introduction	57
3.3.2	Design Optimisation	58
3.3.2.1	Multi-Disciplinary Optimisation	60
3.3.2.2	Multi-Objective Optimisation	62
3.3.3	The influence An Objective Function Has On The Chosen Solution	64
3.3.4	Need For An Improved Objective Function	67
3.3.5	Surplus Value Development	71
3.3.5.1	The Surplus Value Equation	74
3.3.5.2	A Review Of The Surplus Value Objective Function	78
3.4	Models	80
3.4.1	Metamodel	81
3.4.2	Design Of Experiments	83
3.4.3	Creation Of Response Surface Model	86
3.4.4	Techniques To Improve Goodness Of Fit	91
3.5	Summary	91
	Chapter 4: Value	93
4.1	Defining Value	94
4.2	Creating The Correct Value Function	99
4.3	Summary	116
	Chapter 5: A New Framework: Value Seeking System Design (VSSD)	117
5.1	The Value Seeking System Design (VSSD) Methodology	117
5.2	Summary	132
	Chapter 6: Design Problem And Model Overview	133
6.1	Design Problem	134
6.1.1	Design Problem Overview	134
6.1.2	Design Mission	135
6.1.3	Aircraft Utilisation	136
6.1.4	Aircraft Operational Region	138
6.1.5	Load Factors	139
6.1.6	Aircraft configurations	141
6.2	Research Model	143
6.2.1	Model Creation	143

6.2.1.1	FLOPS (FLight OPTimisation System)	144
6.2.1.2	ALCCA (Aircraft Life Cycle Cost Analysis)	146
6.2.1.3	Passenger Space Model	146
6.2.1.4	Surplus Value Model	148
6.2.1.5	Evaluation Of Each Design Concept	151
6.2.2	Model Assumptions.....	152
6.2.3	Metrics.....	154
6.2.3.1	Performance Metrics	155
6.2.3.2	Economic Metrics.....	156
6.2.3.3	Social Metrics	158
6.4	Summary	160
Chapter 7: Discussion & Results		162
7.1	The SE, VDD and VSSD Approach To The Design Problem	162
7.1.1	The System Engineering Approach.....	162
7.1.2	The Value Drive Design Approach	167
7.1.3	The Value Seeking System Design Approach.....	169
7.2	Prediction Profiler	174
7.3	Results	178
7.3.1	Selecting The Best Design.....	180
7.3.2	Solution Spaces.....	181
7.3.3	Requirements vs Desirements.....	186
7.4	Refuel Study	189
Chapter 8: Conclusions		195
8.1	Aim And Objectives Review	195
8.2	Novel Contributions To The State Of Art	204
8.3	Future Work	205
8.4	Concluding Remarks.....	206
References.....		207

List of Figures

Figure 1 – The System Engineering Approach Defined By The Department Of Defense [4] ...	8
Figure 2 – Requirement Decomposition And Allocation Example [4]	11
Figure 3 – Notional Physical Decomposition Of An Aircraft At Conceptual Level [29]	12
Figure 4 – The Value Driven Design Process [61].....	22
Figure 5 – Solution Space Comparison Between SE (a) And VDD (b) Techniques [72].....	30
Figure 6 – Trend Of Design knowledge, Cost Committed And Designer Freedom [73]	44
Figure 7 – A Triangular Fuzzy Logic Membership Function	48
Figure 8 – Possible Fuzzy Logic Membership Functions	48
Figure 9 – Membership Function Of Boolean Logic.....	48
Figure 10 – Thermal State Of A Room Characterised By Boolean And Fuzzy Logic [78]	49
Figure 11 – Comparison Of Need Captured Through Boolean And Fuzzy Logic.....	51
Figure 12 – Stakeholder Speed Preference.....	54
Figure 13 – System Speed Preference Defined By Fuzzy Logic.....	55
Figure 14 – Acceptable Solution Space Defined By Boolean And Fuzzy Logic.....	56
Figure 15 – How The Objective Function Alters The Selected Design [67].....	65
Figure 16 – Face Centred Central Composite Design (3 Factors) [127]	86
Figure 17 – Variable Screening Test.....	87
Figure 18 – Actual Vs Predicted Plot.....	89
Figure 19 – Example Of A Good Residual Plot	90
Figure 20 – A Systematic Approach For Creating A Value Function	99
Figure 21 – House Of Quality [137].....	105
Figure 22 – Typical System Quality Scale	108
Figure 23 – House Of Quality For Family Car Example	114
Figure 24 – Car CO ₂ Desirability Factor	115

Figure 25 – Value Seeking System Design Methodology	118
Figure 26 – Stakeholder Top Speed Design Desirability Function	123
Figure 27 - A Systematic Approach To Creating Design Desirability Functions	125
Figure 28 – Comparison Between The SE, VDD And VSSD Techniques	131
Figure 29 – Visual Representation Of Mission Segments	135
Figure 30 – Monte Carlo Simulation For Economy Passenger Demand	140
Figure 31 – Assumed Economy Load Factors Based On Aircraft Capacity And Demand.....	141
Figure 32 – Overview Of Research Model	144
Figure 33 – Visual Representation Of The Passenger Space Model	147
Figure 34 – Airfare Vs Flight Distance	149
Figure 35 – Aircraft Seating Arrangement	150
Figure 36 – Acceptable Airline Operating Costs Defined By System Engineering	165
Figure 37 – Acceptable Airline Operating Emissions Defined By System Engineering	166
Figure 38 – Corresponding Desirability Function For Each Desirement	171
Figure 39 – House Of Quality Generated Through The VSSD approach	172
Figure 40 – Metamodel Prediction Profilers.....	178
Figure 41 – Solution Space Created By Each Technique	182
Figure 42 – The Effect Of Varying Design Range On The Solution Space	184
Figure 43 – The Effect Of Varying Aircraft Passenger Capacity On The Solution Space	184
Figure 44 – Stakeholder Needs Represented As Requirements And Desirements	187
Figure 45 – Total Passenger Need.....	188
Figure 46 – Results Comparison Between Design A And Design B (Refuel Study)	192
Figure 47 – Annual Comparison Between Design A And Design B (Refuel Study).....	193
Figure 48 – Pricing Structure (Refuel Study)	194

List of Tables

Table 1 – Beneficial Characteristics To Be Retained Within New Design Technique	32
Table 2 – Common Subjective Needs From Stakeholders	50
Table 3 – Representative Number Of Trips Per Year Depending Upon Flight Range [117]... 75	
Table 4 – DoE Full Factorial Experiment (Three Factors, Two Levels And One Response)....	84
Table 5 – Target Values Of New 150 Passenger Aircraft	135
Table 6 – Envisaged Aircraft Utilisation	138
Table 7 – Envisaged Airline Operations	138
Table 8 – Economy Load Factor Examples.....	141
Table 9 – ALCCA Economic Assumptions	152
Table 10 – Additional Economic Assumptions.....	153
Table 11 – Summary Of Envisaged Airline Operations And Pricing Structure	153
Table 12 – Material Assumptions And Learning Curve Based On FCOMP.....	154
Table 13 – Basic Customer Needs Defined By System Engineering.....	163
Table 14 – Additional Aircraft Requirements Defined By System Engineering	163
Table 15 – Airport Regulations Defined By System Engineering	163
Table 16 – Acceptable Cabin Layout Defined By System Engineering.....	164
Table 17 – Acceptable Airline Operating Costs Defined By System Engineering.....	165
Table 18 – Acceptable Airline Operating Emissions Defined By System Engineering	166
Table 19 – Surplus Value Constants.....	168
Table 20 – Discount Multiplier Input Values.....	168
Table 21 – Desirements Defined By Value Seeking System Design	170
Table 22 – VSSD Baseline Values For Value Function	173
Table 23 – Design Variables And Responses For Metamodel.....	176
Table 24 – Results Of Study	179

Table 25 – Airliners Envisaged Flight Operation (Refuel Study)	190
Table 26 – Design Comparison (Refuel Study).....	190
Table 27 – Stage Lengths For Refuelling (Refuel Study)	191
Table 28 - Comparison Between SE, VDD And VSSD Approaches	204

Nomenclature

Abbreviations

ALCCA = Aircraft Life Cycle Cost Analysis

DOC = Direct Operating Costs

DMOD = Development Manufacture, Operation, Disposal

DR = Design Range

FAA = Federal Aviation Administration

FLOPS = Flight Optimisation System

INCOSE = International Council on System Engineering

LCC = Life Cycle Costs

MDO = Multi-Disciplinary Optimisation

NASA = National Aeronautics and Space Administration

NPV = Net Present Value

SE = System Engineering

VDD = Value Driven Design

VE = Value Engineering

VSSD = Value Seeking System Design

Symbols

C_D = Research and Development Costs

C_{Disp} = Disposal Costs

C_{DOC} = Direct Operating Costs

$C_{D\&C}$ = Flight Delay and Cancellation Costs

C_E = Externally Costs

C_{IOC} = Indirect Operating Costs

C_M = Manufacturing Costs

$f(x)$ = Objective Function

F_y = Annual Utilisation

$N_{A/C}$ = Total Number of Aircraft to be Produced

P_{Cap} = Passenger Capacity

P_{Fare} = Economy Passenger Ticket Price

r = Airline Discount Rate

r_c = Customer Discount Multiplier

r_p = Manufacture Discount Multiplier

RP = Reservation Price

SV = Surplus Value

SV_2 = Surplus Value (number indicates ranking position, 2nd highest in this instance)

x = System Attribute

x_{Baseline} = Baseline Attribute Value

Chapter 1: Introduction and Motivation

This chapter introduces the motivation behind developing an improved design methodology within a value paradigm for creating complex systems. The chapter begins by outlining the goal of engineering design process as well as the problems associated with rising complexity. As a means of developing complex systems, two state of the art methods are introduced. However, while both techniques have their advantages, they also have their limitations, prompting the need for a new methodology.

1.1 The Engineering Design Process

The goal of engineering design is to devise a novel solution to a new or existing problem. [1] [2] The aim is to fulfil the needs of stakeholders without violating any of the constraints placed upon the solution. [3] At this point it is important to define both a constraint and a stakeholder to provide clarity. A constraint is a restriction under which the solution must be found [4]. For instance, the solution must not exceed a certain price. Constraints are not requirements which describe what the system must do. Stakeholders are people who have influence on the system design, either directly or indirectly and can come in a variety of sizes, forms and capacities. [5] Typical stakeholders include the end user, the financial backers, regulatory authorities and the public but the complete list is dependent upon the need(s) of the final system. While the premise of design is simple, producing a suitable solution is not so straight forward, as design is both a scientific and a creative approach [6] to problem solving. Furthermore, not all of the information is known at the start of design process; with additional information and knowledge only gained as the design process progresses which may require the current needs and constraints to be updated. [2] As a

result, it may take numerous iterations to produce a suitable solution, [1] [2] assuming one exists.

It is also important to remember that the engineering design process does not create any solutions; instead it is a framework to assist designers arrive at the final solution. [2] The engineering design process is in truth a methodical series of steps. [1] [2] [6] While each design process is different, they generally begin with problem identification and conclude with a final solution. [2] Regardless of the steps involved, a good design process will assist designers through this journey (problem identification to final solution) creating solutions that meet the needs of stakeholders and do not violate any of the constraints.

1.2 What Is A System?

In the broadest sense a system is a collection of two or more elements that are interconnected, interdependent and working together to achieve a common goal, function or purpose. [7] The human body for example is a system, so too is a business, as they both have multiple elements that are interconnected, interdependent and working together to achieve a common goal, function or purpose. If these conditions are not met, it is not a system. While there are numerous examples of systems that form in nature e.g. ecosystems, climate systems, etc the focus of this research is on man-made systems such as aircraft, ships etc. With this in mind this research will use INCOSE definition of a system:

“An integrated set of elements that accomplish a defined objective. These elements include products (hardware, software, firmware), processes, people, information, techniques, facilities, services, and other support elements”. [8]

1.2.1 The Trend Of Growing System Complexity

Today the demands and expectations from stakeholders are higher than at any point in the past and are continuing to grow. [9] As a consequence, design solutions are becoming

increasingly complex [10] and show no signs of reversing. The car key, for example, was once just a cut piece of metal used to unlock or lock a car door. Today they allow keyless remote entry and locking, store driver-specific settings and are used to disengage the immobilization of the engine. While this example demonstrates how a once simple device has become complex, the trend of increasing complexity is also occurring for already complex systems. The mobile phone, for instance, was once a relatively simple device compared to today's standards. When it was first created, its only function was to make and receive phone calls on the go. Nowadays mobile phones are expected to perform this task as well as be an out of office computer and a personal entertainment device. As the demands and expectations from stakeholders continue to grow [9] so too will the level of complexity within future systems.

1.2.2 System Complexity

While complexity is not a new characteristic when designing systems, it is hard to precisely define, as Young et al [11] paper highlights. A working definition of complexity can be considered as a system with many parts that interact with each other in many ways. Although challenging to define, one of most often cited attributes of complexity is that it makes the process more difficult. [11] [12] Complexity is also noted to be an unwanted feature of system design and is often blamed for system problems or failure. [13] [14]

There are many factors which can contribute to the complexity of developing a system, some of which will now be discussed. While this discussion is by no means extensive, its purpose is to highlight the various aspects in which designers encounter complexity within the design process. Adding functions to a system, for instance, ultimately increases the complexity of the task as there is more aspects to consider during the decision making process. Similarly if a replacement system has to improve on multiple aspects simultaneously, this too also increases the complexity of the task, especially if the requests

are conflicting. While this demonstrates complexity from a problem point of view, designers also encounter complexity from the system itself. Systems are too complicated to be developed by one person [15] as they consist of numerous components and subsystems that are interconnected and dependent upon each other. [16] As a result, systems require the collective effort and expertise of many teams, often including cultural and linguistic diversity from around the world, all of which add to the complexity of developing a system. Additionally as the number of components and subsystems within a system increases it becomes more difficult to understand or predict the behaviour of the final system as the inner system interactions become more complicated. This may result in emergent behaviour occurring, behaviours resulting from inner system interactions which cannot be predicted by observing the systems components and subsystems individually, which further increases the complexity of developing a system. [16]

Although all of these factors increase the complexity of the design, the point at which a system transitions from simple to complex system is difficult to define. Sage and Rouse [17] however do provide an overview of when a system is complex based on their study of literature.

“A system is complex when we cannot understand it through simple cause-and-effect or other standard methods of systems analysis. A system is complex when we cannot reduce the interplay of individual elements to the study of the individual elements considered in isolation. Often, several different models of the complete system, each at a different level of abstraction, are needed.”

Magee and de Weck [18] however provides a more succinct definition of a complex system and is the definition taken within this research for a complex system.

"A system with numerous components and interconnections, interactions or interdependencies that are difficult to describe, understand, predict, manage, design, and/or change."

1.2.3 Problems Associated With Growing System Complexity

Developing complex systems has always been a challenge. Rising system complexity however also increases the size, cost, schedule and risk of a developing a system, making this task more difficult to complete on time and budget. [12] [19] [20] Evidence of this can be seen through the growing number of complex systems being associated with design delays and cost overruns, both of which overshadow the systems achievement and cause great dissatisfaction from stakeholders. Worryingly, the trend does not appear to be specific to one industry with numerous, well documented, examples easily found within the aerospace (NASA programs [21]), aviation (Boeing 787 [22], Airbus A380 [23]), automotive (General Motors Chevy Volt [24]) and defence sectors (US Defence Department [25]).

More concerning, however, is that this trend is not new, as Augustine's studies [26] from the 1970's and 1980's show; even back then complex systems regularly overran in cost and time. This implies that the existing methods currently employed to develop complex systems have their limitations and there is need to develop an improved design methodology before these problems escalate out of control.

1.3 Development Of Complex Systems

Traditionally large complex systems have been developed using the System Engineering (SE) technique, which is a requirements based process. The process was created as a means to manage complexity and reduce risk in the development large scale system. [4] Although the technique is well practiced and has proven repeatedly that it can assist designers develop complex systems, the process does suffer from a number of inherent issues which advances

in technology have not been able to solve. Due to these limitations several researchers within the Systems Engineering community began to seek an alternative approach to develop complex system. The Value Driven Design process is one such method and one which is increasingly being discussed within the aerospace industry as a viable alternative to SE. The VDD process however, like SE, has its limitations.

The following sections provide a detailed review of both the SE and VDD techniques, highlighting the advantages and limitations associated with employing each method. This review also examines why the Value Driven Design process has emerged and why the business community has been reluctant to apply it.

1.3.1 System Engineering (SE)

This section focuses on the current System Engineering process. It begins by providing some background information about the technique before detailing the generic steps involved within process. The section concludes by highlighting the advantages and limitations of approach.

1.3.1.1 An Introduction To The System Engineering Process

In the 1950's a new design method known as System Engineering (SE) was developed to assist designers create complex systems. [4] The approach's unique ability to systematically decompose and structure large complex systems into smaller more manageable problems [4] is still seen by many as the best method to develop these systems. Its well-structured, methodical and interdisciplinary approach which considers the complete life cycle of the product [4] is in part one of the many reasons designers still use the technique today.

Three of the most predominate advocators of the SE technique are the International Council on System Engineering (INCOSE), [27] the National Aeronautics and Space Administration (NASA) [28] and the US Department of Defense (DoD) [4]. Although the

System Engineering process is an accepted industry technique, its definition varies between different organisations. The following definitions from INCCOSE, NASA and the DoD highlight this fact but the central theme of SE being an iterative, interdisciplinary design procedure which uses requirements to drive design decisions remains the same.

INCOSE: *“System Engineering is an interdisciplinary approach and means to enable the realisation of successful system”* [27]

NASA: *“System Engineering is a logical system approach performed by multidisciplinary teams to engineer and integrate NASA’s system to ensure NASA products meet customer needs . . . It requires the application of a systematic disciplined engineering approach that is quantifiable, recursive, iterative and repeatable for the development, operation, maintenance and disposal of systems integrated into a whole throughout lifecycle of a project or program.”* [28]

DoD: *“System Engineering is an interdisciplinary process that evolves and verifies an integrated, lifecycle balanced set of system situations that satisfy customer needs”*
[4]

1.3.1.2 The System Engineering Process

Systems Engineering is a requirements driven approach where the main focus is to transform requirements into a design without violating stated constraints. [4] Similar to the definition of SE, the SE process varies slightly according to different institutes. Each SE process however follows the same general principles of verification and validation implying that they are simply different adaptations of the same process. To describe the System Engineering approach, this research will use the SE process developed by the US Department of Defense (DoD). This however is only a brief overview of the process and more details can be found in Ref [4].

Figure 1 illustrates the System Engineering process developed by the DoD.

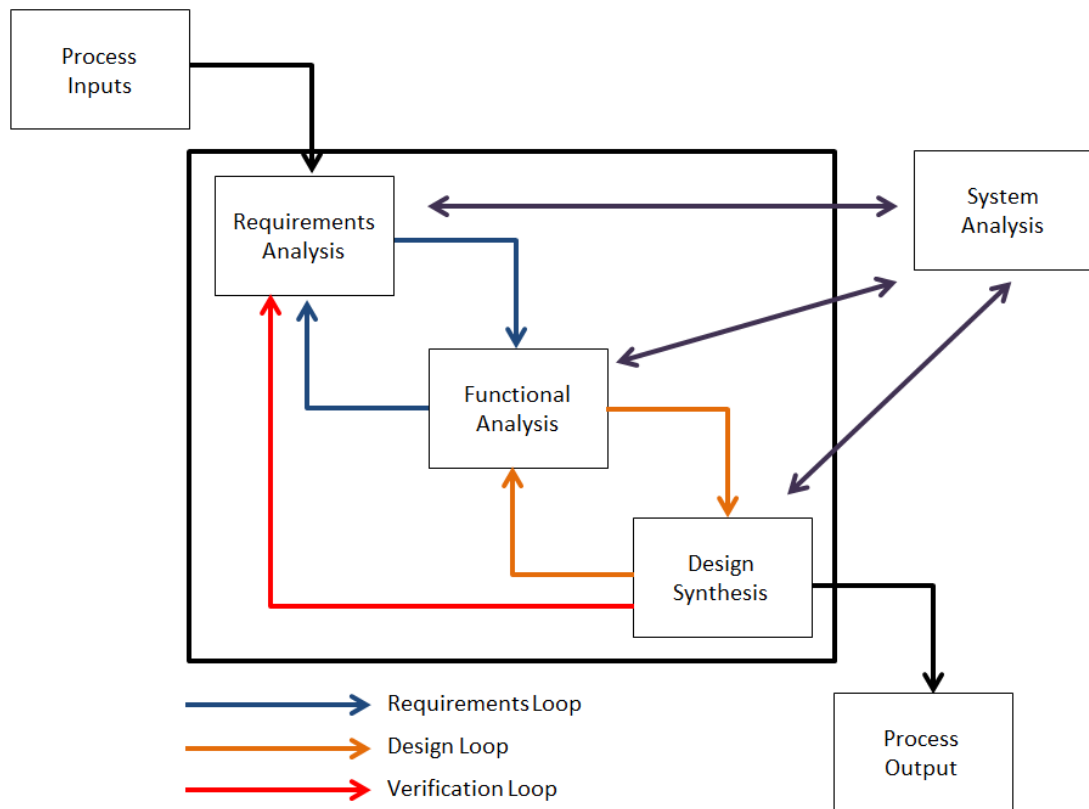


Figure 1 – The System Engineering Approach Defined By The Department Of Defense [4]

The DoD adaption has three main tasks, excluding the process inputs and output. The main tasks are:

- 1) Requirement analysis
- 2) Functional analysis and allocation
- 3) Design synthesis

Since the nature of design is iterative, these tasks are linked via feedback loops rather than being sequential steps; to ensure the design generated meets the required needs. The three feedback loops are also shown in Figure 1 and are known as the requirements loop, design loop and the verification loop. While these are the main tasks and loops of the DoD approach, there is also continuous system analysis activities being performed throughout

the process to support the evaluation of alternatives and the decision making process. System analysis activities include trade studies and system/cost effectiveness analysis as well as managerial tasks such as risk analysis. Tools used to provide input information for analysis activities include modelling, simulation, experimentation and testing. [4]

The main inputs into the System Engineering process are stakeholder needs and system constraints as well as assumptions about the environment the system will be operating within, the associated technology base and standards/regulations applicable when the system is entered into service. Stakeholder needs at the beginning of a design project however are usually vague and high level. For example the system needs be “fast”, “easy to use” and “affordable”. While the language used within this statement is simple and easy to understand it is nevertheless subjective making it unsuitable to base design decisions upon. To overcome this issue, stakeholder needs are transformed into clear, achievable and verifiable high-level requirements that can be used to guide system development. This transformation process is often challenging but vital to the success of the system, [27] as it will be these requirements that will be used to drive the design decisions. Although the requirements are elicited from the system stakeholders, the systems engineer is heavily involved in this process; assisting stakeholders to state them in terms that are complete, unambiguous and quantifiable, to reduce the level of risk associated with the design. [4]

Once this is complete the stakeholder requirements, along with the system objectives, assumptions and constraints, are then fed into a requirements analysis to firstly consolidate these inputs into a cohesive list of customer requirements before transforming them into a list of system functional and performance requirements, which effectively defines what the system must do and how well it must do it. The list of functional and performance requirements are the main outputs of the requirement analysis and become the inputs to the functional analysis and allocation task.

During the functional analysis and allocation task system level functions are decomposed into lower-level functions, to create a functional architecture of the system. Major benefits of performing this task include an increased understanding of what the system must do and how well it must do it as well as highlighting conflicts between functions which will have to be traded off or compromised to generate a viable solution. [27] Once the system level functions have been flowed down, the performance requirements associated with these functions are then flowed down to lower level functions.

The flow down process happens sequentially, one level at a time, to ensure that no requirement is forgotten or missed. Requirements can be flowed down without modification or through allocation. An instance where requirements can be flowed down without modification is if the lower level is responsible for providing that system capability. For example, requirements relating to aircraft communications could be flowed down from system level to become the requirements of the aircraft communication subsystems without modification. Allocation is the quantitative distribution of a higher level to a lower level in which the unit of measure remains the same. Common examples of this include power or mass. Figure 2 illustrates requirement allocation for a system which must not exceed a mass of 1000 kg but includes three subsystems. In this example the subsystems have been allocated their own maximum mass requirement (i.e. 300 kg, 500 kg, 200 kg) which when combined together does not exceed the system requirement (1000 kg). The decomposition and allocation of requirements is recorded as a parent child relationship to provide requirement traceability. Requirement traceability allows the system engineer to quickly determine what effects any proposed changes in requirements would have on related requirements. [27]

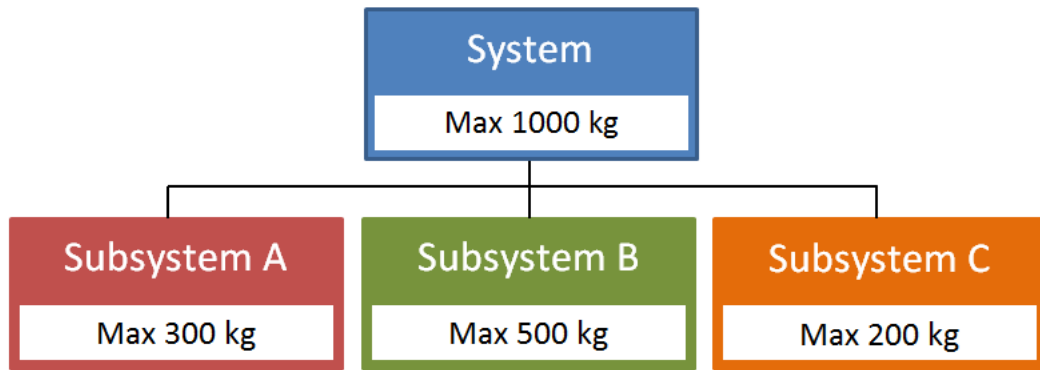


Figure 2 – Requirement Decomposition And Allocation Example [4]

It may be discovered that some functions required by the system are missing or that some requirements are poorly defined during the functional analysis and allocation phase. [4] As a result, the process should return to the requirement analysis to ensure every function identified can be traced back to a requirement. This process is known as the requirements loop and is illustrated on Figure 1.

The objective of design synthesis is to create a physical architecture of the system, capable of performing all of the functions to the required performance level, established in the functional analysis and allocation task. [27] The physical architecture describes the system to be built in physical terms and is the basic structure used for generating specifications and baselines. A simplified physical architecture of a military aircraft is shown in Figure 3 but in reality it would have between seven and ten levels and thousands of individual components.

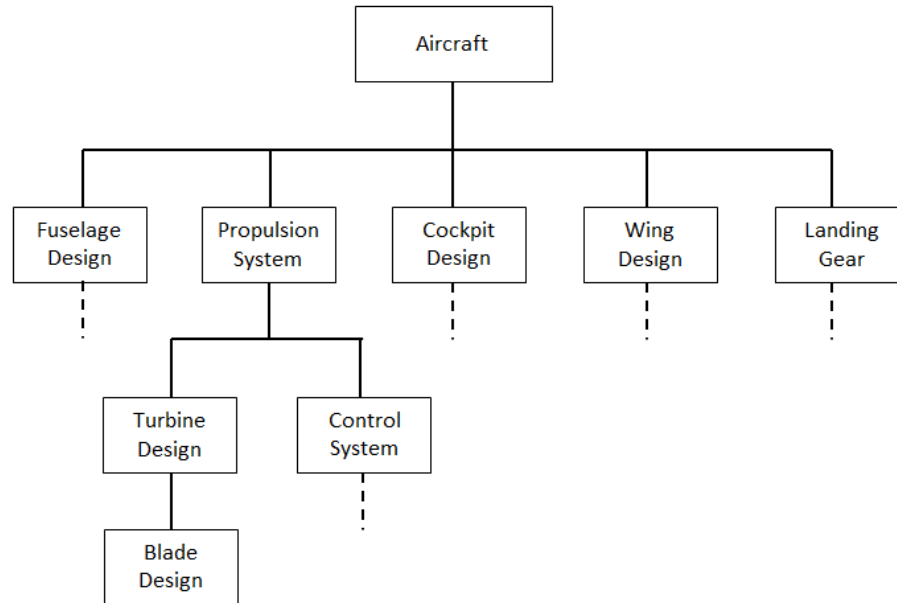


Figure 3 – Notional Physical Decomposition Of An Aircraft At Conceptual Level [29]

To verify that the physical system can achieve the required functions at the desired levels of performance, the design returns to the functional analysis via the design loop. Similar to the requirements loop this process may require some iteration. When this is complete concepts are analysed against the process inputs with the chosen design ending the System Engineering process.

1.3.1.3 Advantages And Limitations Of The System Engineering Approach

The Systems Engineering approach offers both advantages and limitations. The aim of this section is to provide an insight into the factors which have made the process so dominate, especially within the aerospace industry, as well as highlight the reasons why some authors are calling for an alternative approach to be created to develop complex systems.

Advantages of Systems Engineering

One of the biggest advantages of the System Engineering process is that it has, arguably, a proven record of being able to develop a complex system. Without the system engineering process, many of the complex systems which society takes for granted today would not be

possible. Modern aircraft, ships, mobile phones, bridges and buildings have all been designed via the System Engineering process.

Secondly the System Engineering technique is a holistic approach to system design [16] [30]. While all design processes aim to create a viable solution to a particular design problem, a holistic approach considers from the beginning how the system elements (components and subsystems) come together to create the final system, avoiding unnecessary reworking due to incompatible system elements.

The approach also considers the complete life-cycle during the decision making process [28] reducing the risk that a trade-off could potentially become poor later within the life of the system. For instance reducing the costs within one phase (e.g. manufacturing) will be deemed poor if the savings are eroded and become additional costs in another (e.g. maintenance).

Through the utilisation of requirements the technique is able to remove any ambiguity within the stakeholder needs; providing designers with clear design targets. This makes the decision process much easier as everyone involved understands what is expected and deemed acceptable before design concepts are generated.

The technique has the ability to decompose and structure large complex systems into smaller more manageable problems. [4] This allows multiple design teams to tackle different aspects of the system at the same time, irrespective of team's location, reducing the system's development time. It also avoids the necessity for design teams to be reliant or communicate with one another as provided each team meets the requirements set for their component/subsystem, the combined final system will be acceptable.

The technique has also shown that, when it is implemented correctly, it has potential to produce better designs and cost savings throughout the system lifecycle [28] [31] as well as reducing the time taken to go from conception to market [8].

A final benefit of using the System Engineering technique is that provides a simple and intuitive evaluation method for determining if the design is acceptable or not . [8] If the concept passes all requirements, the design is acceptable. If the concept fails to meet one or several requirements, the concept is unacceptable. While concepts that fail requirements are unacceptable, the failed requirements do inform the design team which accepts of the concept need modifying, along with the margin, for the design to become acceptable.

Limitations of Systems Engineering

While these are the key benefits of employing the System Engineering technique there are areas which could be improved within the process.

Firstly the success of the design is highly dependent upon the requirements defined at the beginning of the design process [16]. Any change to a requirement can incur heavy penalties in system resources e.g. time, cost and personnel to correct [32] which will inevitably affect the overall success of the design. Accidentally placing unrequired or poorly defined requirements at the beginning of the process can unintentionally constrain the designers to a rigid solution space which may not include the best solution. If system level requirements are identified incorrectly it will cause lower level system requirements (i.e. subsystems and components) to be derived incorrectly too, [33] further compounding the error. Furthermore it is also often assumed the complete list of system requirements are identified before design concepts are generated. This however is virtually impossible to achieve as some requirements may only become known to the design team during the development process.

Secondly the focus of the designer shifts from finding the best solution for the customer to finding a design which meets all requirements. Although this is may be believed to be sufficient or the same; the reality is, it is not. To highlight this consider any racing championship. Each team will have a design that passes all of the racing requirements but there is only one design which will be the best.

Additionally the System Engineering process assumes a system can be decomposed into numerous subsystems and components, be designed independently and then recombined without losing any design capability or value. [34] This assumption however forgets that as system complexity increases the interactions between the various subsystems becomes more obscure leading to performance or behaviour problems which are impossible to predict by simply studying the system components individually. This phenomenon is known as emergent behaviour and is often unwelcome or undesired. When undesirable emergent behaviours occur they are a real challenge for engineers to overcome and may require significant rework to eradicate.

Designers have always strived to find the best solution for their customers and since the design of these components/subsystems is done isolation, designers will endeavour to optimise their own design within the constraints they have been given in the belief that if their design is optimal the final system will be optimal as well. This isolated view however may only create optimal components and/or subsystems as an optimal system does not require all subsystems and components to be at their optimal, a point many fail to realise. [27] In fact, the belief that every component must be at its optimum only increases the cost and the length of time required to develop the system. [27]

To receive the benefits of cost saving [28] and reduced development times [8] the System Engineering technique must be applied correctly. The numerous examples of complex

systems running over in both time and cost however imply that the correct application of SE is at best difficult and at worst unachievable.

And finally, although the technique has a simple and initiative exit criterion, i.e. when all requirements have been met the design is complete, the exit criterion is itself a weakness of the process. Firstly the process has no universally accepted method of determining which concept is better or the best if more than one concept passes the list of requirements and no design dominates. When this occurs the decision relies completely on the opinion of the decision maker. Secondly the necessity to meet all requirements automatically rejects solutions which do not achieve this, regardless of the magnitude they fail by. There may be instances where a solution does not pass all requirements but better serves the stakeholders needs. For instance there is a system that barely fails a weight requirement but passes all other requirements and is significantly cheaper than any other system. Would this system not be better? The pure System Engineering process does not encourage this discussion as its goal is to find a solution which passes all requirements.

Therefore while the System Engineering approach is a well-structured and methodical process to system realisation, it is clear from the limitations cited above that the process still has some areas needing addressed. While the fundamental principles of the approach have not changed since its creation, the approach is neither reluctant nor resistant to change. The approach is instead an evolving technique willing to incorporate or adapt to new ideas or technologies, if they improve the current practice. One example of this is the adaption of new supporting technologies, particularly within the computer aided design area (CAD, FEA and CFD). These software packages are now common supporting technologies within the SE process because they aid in the development of complex systems by bringing design knowledge forward, allowing better more informed decisions to be made earlier by the designer, which in turn lowers project risk.

In an effort to improve the techniques ability to adapt to growing system complexity, Sheard [35] has suggested supplementing the current SE practice with new principles learnt within complexity theory.

1.3.1.4 Complexity theory

Complexity theory is a theoretical framework that aims to explain complex phenomena not explicable through traditional scientific theories. [35] Sheard [35] believes that if system engineers had an understanding of complexity theory, it would allow them to perform their roles differently and better. Sheard [35] highlights that engineers who are aware of complexity theory would be more prudent in their decision making, as they would better understand that their choices are not made in isolation but instead have lasting consequences that may affect other teams. They would also be more conscious that a change, regardless of magnitude, could have a significant effect on the system and/or other teams; the consequences of which should be investigated thoroughly, for the whole system, before making a final decision. Versing system engineers in complexity theory would also enable improved handling of changing requirements and identifying and managing risks. Assuming requirements remain static or stable throughout the development process is an oversimplification within the current approach. By emphasising they change, the change management process becomes a continuous and purposeful activity instead of being perceived as an unwanted reactive value eroding task.

While all of these things are beneficial and would improve the current system engineering approach, it does not resolve all of the issues cited above. For instance even if all requirements were identified and defined correctly, the process still has no method for determining which design option is best or which system is best for stakeholders. It was due to these limitations that researchers began to seek an alternative approach to developing

complex systems. The Value Driven Design technique maybe one such method and will now be discussed.

1.3.2 Value Driven Design (VDD)

In the past it was common for design solutions to be driven by performance and cost metrics bound by a set of requirements. In search of an improved design process, there has been a call for a move in new direction. It has been proposed that design solutions should be focused on creating value, with design decisions based upon the complete life-cycle of the system. This change in design philosophy has prompted growing interest from research bodies about using value-centric design approaches. [36] [37] [38] [39] In the next few sections, value, especially in the context of system design, is discussed, followed by an introduction to the concept of Value Driven Design.

1.3.2.1 Value

Implicitly, value is a key consideration when engineers make design decisions. [40] As a result a value analysis is always performed before making a decision, even if it does not follow a formal procedure. While there have been many frameworks and methods proposed by several authors to assist in this process since the 1970's, there is still no universally accepted definition of value, what characteristics it has or how stakeholders define the value of an engineering system. [41]

When Miles [42] first introduced the value analysis concept, the value of a system was considered to be good if it had the necessary functions at a low cost and was considered poor if the system lacked performance and had a high cost. Miles' definition of value is therefore a ratio of performance over cost, represented mathematically in Equation 1.

$$\text{Value} = \frac{\text{Function}}{\text{Cost}} \quad (1)$$

According to this definition, a system's value is increased by improving the system's technical performance or by reducing system costs. Although this definition of value encourages designers to eradicate unnecessary costs without removing essential functions, many authors have concluded that Miles definition of value is too simplistic and incomplete. As a result many authors have attempted to provide a more complete definition of value, particularly in the in the fields of marketing and business management. These definitions can be classified into two broad categories. The first category defines value as the maximum amount a customer is willing to pay for an item [43] [44] while the other the defines value in a more subjective manner, being associated with experience and extrinsic properties such as brand, social status and perceived quality. [45]

Anderson [46], for example, defines value as the

“perceived worth in monetary units of the set of economic, technical, service, and social benefits received by a customer firm in exchange for the price paid for a product offering, taking into consideration the available alternative suppliers' offerings and prices” which is in agreement with the first interpretation of value. Similarly Kelly and Male [47] describe value as

“A measure expressed in currency, effort, exchange, or on a comparative scale which reflects the desire to obtain or retain an item, service or ideal.”

Others however use the more subjective interpretation of value, emphasising the notion of “value-in-use” [48], where the perception of value is not limited to the product performance [49] [50] [51] [52] but derived and determined by the beneficiary, through the use of the system. [53] This subjective aspect of value is also highlighted by researchers in marketing and service logic when they stated “Value is uniquely experientially and contextually perceived and determined by the customer”. [54]

To date the value captured within the Value Driven Design process has predominately been through an economic function, with exemplars using Surplus Value or Net Present Value models. [55] [56] This is a result of some authors envisioning that the best design option should be the result of optimising a financial objective function, and that monetizing all design elements results in a comparative platform. [29]

1.3.2.2 An Introduction To The Value Driven Design Process

The Value Driven Design (VDD) process was created to enable optimisation of large complex systems by ensuring the best choices were made on behalf of the system stakeholders. Although the process evolved from the system engineering technique its shift to pursuing value instead of any design which meets requirements is seen by its founders as a viable and improved alternative to the traditional approach. [56] The VDD process however is not an optimisation technique but rather a framework to allow optimisation to take place [29]. Instead of being constrained by requirements as traditional optimisation techniques would be, the approach removes the necessity to meet requirements, freeing the design from these constrictions and thus allowing them to seek and deliver the highest value design.

Similar to the System Engineering process there are many definitions describing the Value Driven Design technique. Two of the most cited definitions are from Collopy [57] and Collopy & Hollingsworth [29] which are listed below. Although these descriptions have slight differences the theme remains the same of a process which uses a system level objective function to optimise and select the best design for given design problem.

Collopy:

VDD “provides an objective numerical evaluation methodology which is a major improvement over multi-objective approaches because of the clear indications of

which technologies are superior, the balanced consideration of performance and cost and the more accurate attribution of value to the technologies” [57]

Collopy and Hollingsworth

VDD is “a movement that is using economic theory to transform System Engineering to better utilize optimisation so as to improve the design of large complex systems, particularly in aerospace and defence” [29]

At present the US Defence Advanced Research Project Agency (DARPA) [36] and the American Institute of Aeronautics and Astronautics (AIAA) [37] are two of the most avid promoters of value-centric design methodologies within the United States (US), with MIT’s Systems Engineering Advancement research initiative [38] and the Value Driven Design (VDD) [39] Institute being the two main scientific bodies dictated to researching new value driven methods for the optimisation of systems during the conceptual stage. Research studies however are not just confined to the US as there have also been some studies conducted within Europe [56] which aimed at demonstrating the benefits of using value drive design strategies to develop aircraft. Furthermore there are working groups within the International Council on System Engineering (INCOSE) [58] attempting to establish procedures (ANSI/EIA-632) [59] and standards on how to model value within the preliminary design phase. [60]

Before the Value Driven Design process is discussed, it should be remembered that as a design technique the approach is still within its infancy, requiring some much needed work to repeatability and reliably produce the designs which the technique promises to deliver. Two such areas are the exit criterion and how to incorporate aspects which are difficult to accurately capture through a monetary proxy; safety for instance.. If these two issues could be address it would greatly enhance the VDD technique. Nevertheless initial studies of the

approach [29] [56] [57] [61] [62] [63] [64] have shown the potential of the technique and one possible method of avoiding the issues within the System Engineering technique even if at present the process has been difficult to implement.

1.3.2.3 Value Driven Design Process

Value Driven Design follows the cyclic iteration process shown in Figure 4. The process starts in the bottom left quadrant (Definition) and moves clockwise (through Analysis, Evaluate and Improve) with the aim of seeking better value for the system stakeholders with every cycle.

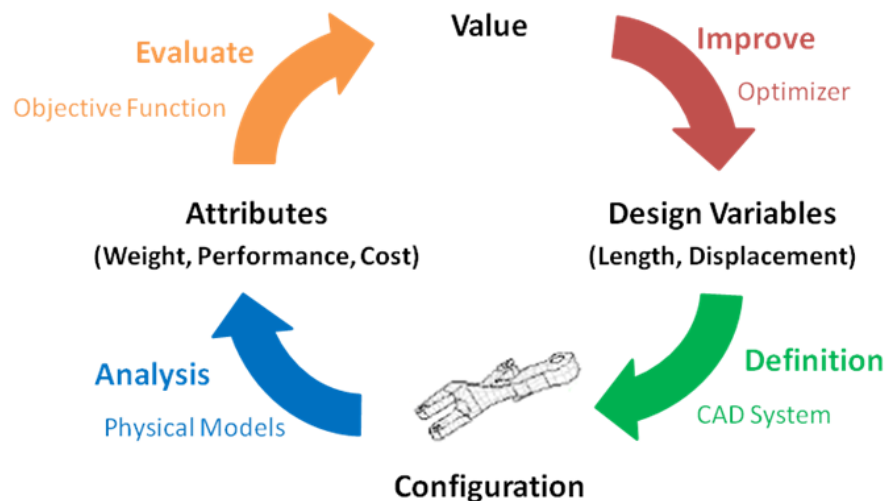


Figure 4 – The Value Driven Design Process [61]

The first step within the Value Driven Design methodology is to define the need which requires a solution. Once the need has been established, the list of stakeholders can be identified. Stakeholders are people who have influence on the system design, either directly or indirectly and can come in a variety of sizes, forms and capacities [5]. The group of stakeholders is therefore unique to each system but common examples include the end users and the systems financial backers. Once the stakeholders have been identified, the final part is to determine the system value which designers will seek to maximise. The definition of system value is at the discretion of the stakeholders but past studies applying

this technique have historically defined value within an economic context [56] [63] [65] [66] [67]. It is important that every party agrees and understands this value as it will be used to create the objective function which will drive the design choices made by the design teams. Although this step has been described in a linear manner, it is in fact cyclical as the identification of needs, stakeholders and the system value can in turn identify more needs, stakeholders and revise the definition of system value. The step is only complete when every party involved is confident all needs, stakeholders and the definition of system value is correct.

After the need and definition of system value have been agreed, the next step is to create physics-based predictive models to assist the design team understand the solution space and optimise the design. Typical simulation tools include Finite Element Analysis (FEA) and Computational Fluid Dynamics (CFD) models, as well as synthesis models for the complete system.

Once this is complete the value model is created which will then be used to evaluate each design option in terms of the value it offers its stakeholders. To create this value model, the design teams begin by selecting a notional design to form a baseline solution. From this baseline, system attributes are identified [29]. A sensitivity analysis is then performed using the models to determine which attributes of the design affect the system's value. System attributes that have a significant effect on the system's value are incorporated within the value model while attributes that have negligible or no effect on the system's value are omitted to reduce the complexity of the model. For the value model to produce a single value score, all attributes must have the same metric. The next task is therefore to transform all attributes incorporated within the value model into a common metric. The major benefit of producing a single value score is that it makes the evaluation criteria intuitive, as the better or best design will naturally have the higher value score. [5]

Once the value model has been created designers begin generating design concepts, with the ultimate goal of finding the solution that returns the highest value score to the stakeholders. After generating a design concept, its value score is determined via the value model. If the concept is the first concept, the concepts value score automatically becomes the baseline value score and become the value score designers seek to improve through further iteration. If a new concept is created which has a higher value score than the original concept, the new concept becomes the preferred design with its value score becoming the new baseline value score. Concepts which are created and have a lower value score than the current baseline concept are rejected as they offer lower value to the stakeholders. After each concept has been generated, evaluated and the appropriate action taken (i.e. accept or reject) the design team have to make a choice on whether to continue the optimisation process or accept the baseline solution as their chosen design.

1.3.2.4 Advantages And Limitations Of The Value Driven Design Approach

Giving designers an environment to freely optimise a complex system without being restricted to a rigid solution space is ultimately the greatest benefit of using the technique. [62] [68] There are however some other useful advantages provided by the approach.

Advantages of Value Driven Design

Firstly design decisions are based on their ability to improve a systems value rather than simply fulfilling a requirement. [29] [56] This focuses designers to create the highest value system for the stakeholders and not just any design that is acceptable within the boundaries of the requirements.

Secondly the optimisation process is unified and performed at a system level. While other techniques encourage optimisation, optimisation in these techniques is often executed at a component or subsystem level; creating only optimum parts. Unifying the optimisation and

performing it at a system level however forces every designer to design their part for the benefit of the system rather than their individual design.

Using a unified system level objective function to evaluate different design options also allows the design process to become more transparent, traceable and repeatable than simply using the experience of the designer to select a design option. The objective function theoretically eradicates the personal opinion/experience of the designer when making decisions as each option is given a single value score from the value model meaning the selected option will remain consistent even if the process is repeated with a different designer.

Designing via a unified system level objective function also enables the design team to avoid falling victim to dead loss trades. A dead loss trade occurs when design teams try to improve their individual component designs but the net effect of these choices is negative on the overall system. [29] For example there are two design teams working on one system but on two different components. One team decides to sacrifice the weight of their component to save money (a 20 lb increase in weight for a \$400 saving in cost). The other team however decides to do the opposite; it spends money on reducing the weight of their component (a 15 lb decrease in weight for a \$1000 increase in cost). Given the components the design teams are working on, these decisions appear to be good choices. After redesigning the components, both teams achieve their goal. Overall however the cost and weight of the combined components has now increased (+\$600 and +5 lb); as the cost increases incurred by the second team is less than the savings of the first team ($-400 + 1000$) and the weight reduction from the second team is less than weight increase of the first team (20-15). Therefore even though both teams believe they have made better components, making the system better, the reality is the system now weights and costs more than the original design.

Disadvantages of Value Driven Design

Although these advantages highlight the significant benefits of employing the VDD technique, the process still has many difficulties to overcome before it will be widely accepted by industry. A summary of these can be found in Soban et al [5]. Two of the most pressing issues, however, is how to design a system without requirements and how to ensure a suitable value model is created.

People intuitively understand the role requirements play within a design process and how they are used to find an acceptable solution. The Value Driven Design process however uses an objective function to perform this task. While the objective function allows the designers to always select the option which gives the stakeholders the most value, it provides no clear design targets for the designer or any assurances to the system stakeholders about the final design, except that the highest value system will be chosen. For instance, stakeholders may articulate that they require a system that can transport 150 passengers. If the value model indicates increasing the number of passengers above 120 passengers erodes overall system value, the VDD process will return a 120 passenger system as the design decisions are based on options that increase value.

While removing the necessity to meet requirements can be seen as a good thing because it no longer constrains the design team to a rigid solution space, the unwanted concomitant of this is that it creates a solution space that is so vast it virtually impossible to obtain the highest value solution given the finite resources of a project.

Furthermore, requirements provide designers with an intuitive metric for knowing when the design was acceptable and complete, a characteristic not currently present within the Value Driven Design technique. Instead the exit criterion is based upon the choice of the designers to continue the cyclic iteration process or not. In this situation the design team

may opt for one of these three options where “x” indicates a number predetermined by the design team before the process began.

- 1) The design process will end when an “x”% increase in value as been achieved compared to the baseline solution.
- 2) The design process will end if no improvement in value is created after “x” attempts.
- 3) The design process will end when the resources i.e. time and money allocated to this process has been consumed.

While these three options could overcome this issue by indicating when the process should stop, none are ideal. For instance purely stopping when a percentage increase in value has been achieved does not ensure the highest value design has been generated as there could be potentially be a higher value design available but the designers failed to seek and deliver this to the stakeholders due to already satisfying their goal. Similarly stopping after “x” attempts because a higher value system could not be obtained seems reasonable but again fails to ensure the highest value design is generated for the stakeholders. Finally continuing until all resources have been consumed, removes the potential of finishing early or saving money, needlessly driving up costs and lengthening the time required to develop the system.

The second major concern designers have with the Value Driven Design technique is the development of the suitable value model, as it will ultimately drive and determine the final design. To date, research has focused primarily on creating economic value functions, with surplus value being the choice of many authors. Surplus value is a simplified economic function that ignores competition effects and is defined as the reservation price (the highest price a customer is willing to pay in the absence of any form of competition) minus the manufacturing cost [69]. The latest form of the surplus value equation is shown in

Equation 2 which has been developed to calculate the surplus value of various aircraft designs.

$$V_s = r_p N_{a/c} \left[r_c F_y (R_{P\&C} - C_{OP} - C_{D\&C} - C_E) - C_M - C_{Disp} \right] - C_D \quad (2) [70]$$

Where V_s is surplus value, r_p the discount multiplier based on a single year's revenue and costs for the manufacture, $N_{a/c}$ the total number of aircraft to be produced, r_c the discount multiplier based on a single year's revenue and costs for the customer, F_y the aircraft's annual utilisation, $R_{P\&C}$ the total airline revenue (for all flights and for both passengers and cargo), C_{OP} the aircraft's total operating cost (both direct and indirect), $C_{D\&C}$ the costs associated with flight delay and cancellation, C_E the externality costs (which is a representation of societal good, currently the costs associated with aircraft noise and emissions), C_M the aircraft's manufacturing costs C_{Disp} the aircraft disposal costs and C_D the aircrafts research and development costs.

The question becomes, is the value of a system purely economic? Ewart et al. [71] states that "values are what stakeholders of the system care about," which implies that these economic functions do not capture a system true value. While the founders of the Value Driven Design technique welcome these inclusions within the value model, the method of achieving this has not been well defined. The complexity of this task arises from the necessity to have every value aspect using the same metric to enable the value model to produce a single value score to provide designers with a simple and intuitive evaluation method. For example if safety was to be incorporated within the economic functions historically used within the Value Driven Design technique it must first be monetised; not an easy or justifiable task.

Defining value in the context of system design and how to create a suitable value model is the focus of chapter 4. The next section however compares the SE and VDD approaches.

1.3.3 A Comparison Between The SE And VDD Techniques

The benefits and limitations associated with applying the System Engineering and Value Driven Design techniques was discussed in the previous sections. This section focuses on the key differences between the two methods highlighting the characteristics which should be retained within a new design process to enhance the current state of the art methods.

Exit Criterion

The first major difference between the two techniques is the exit criterion employed by each approach. The System Engineering approach continues until all of the requirements have been met, whereas the Value Driven Design process continues until the designer decides to stop the design process. Using requirements as an exit criterion also is intuitive yet fairly simplistic, as it does not encourage designers to find the best solution if an acceptable solution has been found. Alternatively continuing until some measure of maximum value has been found does encourage designers to find the best solution but knowing when this has occurred is not intuitive. Finding an exit criterion that is both intuitive and encourages designers to seek the best design is therefore two important aspects which need to be retained within the new design process.

Decision Metric

The second major difference is the mechanism employed when making a decision. The System Engineering approach uses requirements for this task, whereas the Value Driven Design technique uses a system level objective function. While the outcome of each mechanism is intuitive, the system level objective function is the superior option of the two. Basing decisions on requirements only informs the designer if the solution is acceptable and is unable to determine which design is better, if more than one solution meets all of the requirements. The objective function, however, evaluates and rank designs, enabling the highest value option to always be chosen. Applying a system level objective

function also eradicates personal preference of the decision maker and prevents dead loss trades occurring, improving the techniques transparency, traceability and repeatability compared to basing decisions on requirements. Requirements though should not be removed completely either as it is very difficult for designers to design without them. A system level objective function and requirements should therefore be retained within the new design methodology to preserve these benefits.

Solution Space

The third major difference is the solution space created by each technique. To illustrate this Figure 5 considers a simple design problem with two design constraints, weight and cost, adapted from Ref. [72].

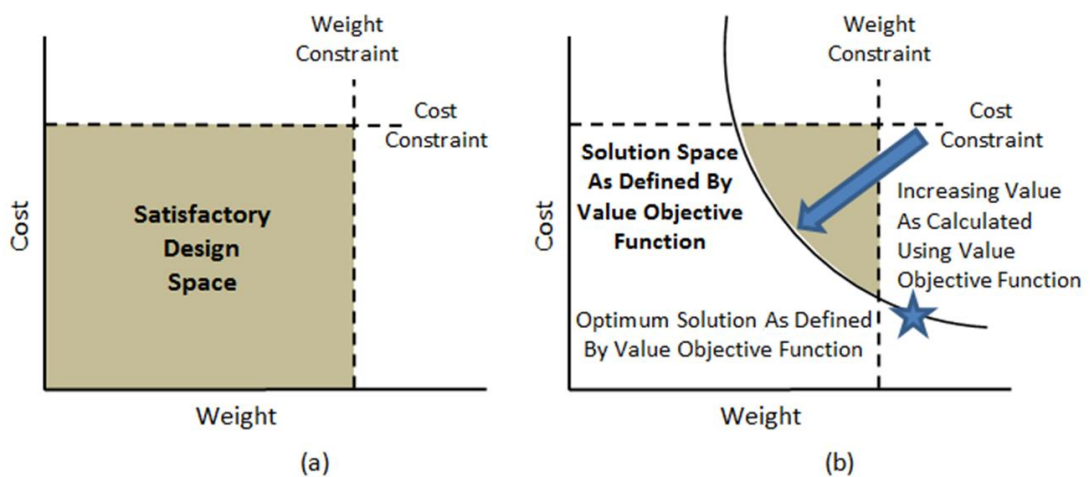


Figure 5 – Solution Space Comparison Between SE (a) And VDD (b) Techniques [72]

Using the traditional Systems Engineering approach, requirements define a rigid solution space (shown as the shaded area in Figure 5a) where all acceptable solutions may be found. Any solution found within this region, no matter of its location, is deemed to be acceptable as it meets the all of requirements. Value Driven Design, on the other hand, is not constrained to a particular solution space but free to explorer for the highest value design, which may lie outside the solution space defined by the Systems Engineering technique (as is the case in Figure 5b). Neither of these solution spaces, however, is ideal. A too rigid

solution space may prevent the designer from delivering the most valuable system, if the system lies outside this space. An open solution space however is virtually impossible to optimise given finite project resources. A possible solution to this issue could be provided if a non-rigid solution space could be created.

Novel System Creation

The final difference between the two techniques is their ability to create novel systems. The utilisation of requirements within the System Engineering has enabled the approach to develop these systems over the past 60 years. By contrast, the Value Driven Design approach can only evolve a design, as designers require a base solution to determine the design variables to use within their value model. The ability of how requirements achieve this should therefore be retained within the new design process.

Selecting between the System Engineering and Value Driven Design techniques therefore bring the designer both benefits and limitations. Designers would benefit from a design methodology which retains the advantages inherent within both the SE and VDD techniques without suffering from their limitations. The creation of just such an innovative design methodology is the focus of this research and aims to provide designers with an improved process for developing complex systems.

Table 1 provides a summary of the beneficial characteristics which must be retained within the new design process. While all of the characteristics are beneficial in their own right, if they can be successfully combined together an enhanced design process will be created for designing complex systems within a value paradigm.

Table 1 – Beneficial Characteristics To Be Retained Within New Design Technique

ID	Beneficial characteristics
01	An intuitive exit criterion
02	Clear design targets
03	Value seeking philosophy
04	Uniform system level optimisation
05	Quantification of value within design option
06	Non-rigid solution space

1.4 Summary

The main focus of the chapter was to understand how the current state of the art techniques assist designers create complex systems. To accomplish this, the various steps involved within the System Engineering and Value Driven Design processes were outlined along with the advantages and limitations of applying each approach.

From the review it was clear that neither Systems Engineering or Value Driven Design offered the desired existing framework to design complex systems within a value paradigm. The use of requirements within the traditional SE technique is ultimately its biggest strength but also its biggest weakness as it constrains designers to a rigid design space without being unable to determine which design option is best for its stakeholders. While the new VDD approach overcomes these difficulties, implementing the technique has its own issues as designers are finding it challenging to design complex systems without meeting requirements. The review identified beneficial elements that, if retained within a new design process, would enhance the current state of art complex system design techniques.

Chapter 2: Research Questions, Hypothesis and Thesis Synopsis

2.1 Research Questions And Hypothesis

Chapter 1 reviewed the current state of the art techniques presently being employed within the aviation industry to develop complex systems. A detailed overview of the System Engineering and Value Driven Design methodologies was presented along with the strengths and limitations associated with applying each technique. From this review it was clear that a new design methodology is required to develop complex. This has led to the following research questions being constructed:

- 1) What are the elements within the traditional System Engineering and Value Driven Design techniques which must be retained or eliminated to enhance the current design processes?
- 2) How does optimising a system through an all-encompassing value function compare to a system which has been optimised using individual objective functions based on performance or economics aspects?
- 3) How should the term value be defined in the context of system design?
- 4) Does the current Value Driven Design objective function adequately capture this definition of value?
- 5) After creating a new design methodology, how does the process and result compare to the traditional SE and VDD approaches?

Taking these questions into account, the hypotheses proposed by this research are:

- *The current surplus value metric employed by the Value Driven Design technique does not adequately capture a design's true value, creating biased value trade-offs.*

- *By incorporating the elasticity of stakeholder desires within the design process, stakeholders are able to communicate the solution they require without restricting the designer to rigid solution space.*

The work presented throughout this thesis aims to answer each of the above questions and assess the validity of these hypotheses. The overall aim of this research therefore becomes:

To develop a novel design methodology which combines the beneficial elements of both the System Engineering and Value Driven Design techniques into a new approach which addresses each other's weakness and ultimately provides designers with a tool which allows them to develop the most valuable system for their stakeholders.

To achieve this aim the following objectives were developed:

- Objective 1:** *Investigate the benefits and limitations associated with employing the traditional System Engineering and Value Driven Design techniques to develop complex systems.*
- Objective 2:** *Investigate the role an objective function has within the design process and understand how they are currently developed and implemented.*
- Objective 3:** *Investigate and develop an understanding of the term value within the context of system design.*
- Objective 4:** *Develop an innovative design methodology which retains the benefits associated with the current state of the techniques (SE & VDD) without suffering from their limitations.*
- Objective 5:** *Benchmark the proposed technique against the current System Engineering and Value Driven Design technique.*

2.2 Thesis Synopsis

The aim of this research is to create an enhanced design methodology that is capable of developing complex systems a follows a value paradigm. The goal is to retain the benefits inherent within the current state of the art approaches whilst minimising their limitations. Chapter 1 provided a detailed overview of these methodologies (SE and VDD) while also presenting the strength and weakness associated with applying each technique. The chapter concluded by highlighting the key elements an improved design methodology must possess if it is to be considered an enhancement over the existing approaches. The remaining structure of thesis is summarised below along with a brief description of the work included within each chapter.

Chapter 3 – Evolution Of Design Framework

Chapter 3 investigates the key elements required within the new design process. Requirements and their role within the design process is examined along with the effects early decisions have on the final design. The theory of fuzzy logic is then introduced as alternative method of capturing stakeholder needs. The role an objective function plays within the design process is also examined in this chapter. A review of the objective functions employed within the System Engineering, Multi-Disciplinary Optimisation, Multi-Objective Optimisation and Value Driven Design practices is presented to enable a discussion on how a suitable overarching value function could be developed for any complex system. The chapter concludes with an overview of response surface models; how they are created, validated and techniques that can be employed to improve goodness of fit.

Chapter 4 – Value

Chapter 4 analyses the term value, especially in the context of system design. To date, value functions employed within the Value Driven Design technique have been purely economic with the surplus value metric the choice of many authors. This chapter investigates if this metric is sufficient or whether another metric should be employed to design towards value. Regardless of this outcome, the chapter concludes by outlining a possible method in which suitable value functions could be created for any complex system.

Chapter 5 – A New Framework: Value Seeking System Design (VSSD

)Chapter 5 outlines the proposed design methodology known as Value Seeking System Design (VSSD). A detailed description of each step is provided with key differences between the current methods also highlighted.

Chapter 6 – Design Problem And Model Overview

Chapter 6 introduces the simplified design problem which will be used to benchmark the proposed technique against the current state of the art approaches. A detailed description of the design problem is presented along with any simplifying assumptions. The comprehensive value model is also introduced in this chapter; which will be used to generate design concepts.

Chapter 7 – Results and Discussion

Chapter 7 details the results of benchmarking the proposed technique against the current state of the art approaches. The chapter demonstrates how each technique faced with same challenge, uniquely transforms this need into a final solution. The process and the result of each technique is then compared to establish if the proposed technique is an enhancement over the traditional approaches.

Chapter 8 – Conclusions

Chapter 8 is the final chapter in this thesis. The key conclusions of this work are presented along with the research novelty and recommendations for future work.

Chapter 3: Evolution Of Design Framework

After reviewing the current System Engineering and Value Driven Design methodologies in chapter 1, it was clear that neither approach offers the perfect framework to design complex systems. It is therefore proposed that a new design approach be created, one which retains the advantages inherent within the System Engineering and Value Driven Design techniques whilst simultaneously addressing their limitations. The chapter begins by briefly reviewing these limitations, highlighting the aspects which the new design methodology aims to address. Following this review, key elements within the current state of art methods will be analysed. The purpose of this investigation is twofold; to firstly understand why these key elements are beneficial to a design methodology and secondly to identify possible modifications to them which would create an enhanced approach. Requirements and their role within the design process is examined along with the effects early decisions and setting initial requirements have on the final design. The theory of fuzzy logic is then introduced as alternative method of capturing stakeholder needs, instead of purely Boolean logic which is presently used to create requirements. The next section in this chapter focuses on the role objective function(s) play within the design process. Why they are used, how they are created and have evolved is discussed, along with the effects their use will have on the selected design. As a modelling environment will be created within this research to assist benchmark the proposed design technique, the final section in the chapter provides a brief overview of models and their use within the design process. It explicitly addresses response surface models; how they are created, validated and techniques that can be employed to improve goodness of fit.

3.1 A Brief Review Of The SE And VDD Limitations

System Engineering is one of the mostly widely known and accepted techniques employed when developing complex systems, but it is not without its issues. Firstly, the technique relies heavily on the use of requirements to define customer needs and determine when the design is complete. While defining needs through requirements removes their ambiguity, it forces the customer to define their complex needs as absolutes, differentiating between what is acceptable and what is not. While this ensures all stakeholders understand what the final system must do, this simplified approach creates rigid and possibly over constrained design space, at a point when the effect of these choices is unknown. Secondly the system engineering approach has no universally agreed method of evaluating different designs or stating which design is best. Instead the process can only inform the design team which designs are acceptable and those that are not. Additionally although the use of requirements allows the large complex system to be decomposed into smaller more manageable sub-systems, individually optimising these subsystems does not guarantee an optimal system because of the techniques non-unified approach to optimisation. It was for all of these reasons that the Value Driven Design technique was developed.

Although the Value Driven Design technique has been seen by its founders as a solution to these issues within System Engineering, it too is not without its concerns. For instance while the removal of or necessity to set and meet requirements may open the design space to allow the design teams to find the most valuable design, designing without requirements is a logistically difficult process to implement, especially when designing complex systems. Furthermore the creation of an appropriate single, all-encompassing system level objective function which is used to base design decisions upon is still within its infancy and is one of the reasons why industry is reluctant to use the approach. Currently the value driven design

technique utilises a purely economic function. While researchers applying the technique welcome the inclusion of the other aspects, they first must be monetised to ensure a single value score. Monetisation of certain aspects however is difficult. One particular example of this is safety; how does a designer begin to or even justify the monetary value they select for safety without it appearing to devalue human life?

Therefore while both the System Engineering and Value Driven Design methodologies offer advantages over each other, it is clear that neither approach offers the desired framework to design complex systems. Requirements assist designers in understanding the need of the stakeholder and allow large complex systems to be broken in small more manageable tasks, while the philosophy of Value Driven Design seeks the one thing stakeholder's want, value. It is therefore proposed that a new design approach is created that retains these benefits while simultaneously addressing the above concerns.

Before the new approach is presented, it is important to understand where the benefits of each process stem from if they are to be considered for retention within the new design methodology. In the case of Value Driven Design, it is through the utilisation of a unified system level value function. Designers base all decisions upon this function, selecting options which increase the systems overall value, rather than optimising subsystems individually on one or a range of possibly different aspects. Using a system level value function is therefore seen as a key tool within the new design process. Value and how to create the correct system level value function is discussed in Chapter 4. The System Engineering process on the other hand owes its success to the use of requirements. Without requirements the design process becomes difficult as designers no longer have clear targets to meet. Requirements are therefore seen as a key and necessary part of the new design process. The role which requirements play within the system engineering is analysed in the next section.

3.2 The Role Of Requirements Within The Design Process

Requirements play an important role within system engineering process, bringing both benefits and limitations. The proposed methodology, however, seeks to remove these limitations while retaining the benefits associated with requirements. To achieve this goal it is important to understand how requirements are currently defined, created and utilised within the system engineering process.

3.2.1 Requirements

At the beginning of the design process, stakeholder needs are often vague and subjective, unsuitable to base design choices upon. To overcome this problem the system engineering process redefines these needs as a list of requirements, which are clear statements to which the system must conform. This is arguably the biggest benefit of using requirements, as they provide designers with clear targets which cannot be misunderstood. This ensures designers understand the needs and expectations from stakeholders, reducing project risk.

Requirement generation is difficult task, even for the most experienced designers. To assist designers in this process INCOSE have developed a list of characteristics that all good requirements should have and are listed below. [37]

- Necessary - If the need can be satisfied without the requirement then it is not necessary
- Verifiable - Can the requirement be objectively verified through a test
- Unambiguous - The requirement can only be interpreted in one way
- Complete - All of the known conditions which the requirement applies under are stated
- Consistent - Requirements can be met without conflicting with one another
- Traceable - The origin of each requirements is known

- Concise - The requirement is stated in simple and clear language with one goal or function
- Achievable - Must be feasible
- Unique - Requirements are not repeated

While these characteristics ensure good requirements are generated, to meet the characteristics of being unambiguous, verifiable and concise Boolean logic is applied to each of the customer's needs. Boolean logic reduces the need of customer into absolutes; clearly defining what is or what is not acceptable. For instance stakeholders may require the system to be "light weight". Light weight, however, is vague and subjective. Transforming this need into a requirement i.e. the final system must weigh less than 10 kg, the designer is presented with an unambiguous, verifiable and concise statement on which design decisions can be made.

Another advantage of defining stakeholder needs like this is that it provides an intuitive method of determining when the design is complete. Only when the design passes all requirements is the solution deemed acceptable and complete, as failing requirements indicate that at least one of the stakeholders needs has failed to be met. While failed requirements are undesirable, they do inform the design team why the design is unacceptable and highlight the aspects of the design which need to be improved if it is to pass the exit criterion.

Defining requirements like this, however, assumes that once they have been agreed, they are set, believed to no longer change, or to change slightly at best, and therefore have little or no significant effect on the final design [4]. For example, a new system is requested to transport 12 people over a given range, this is not expected to change to 150 people as these are two completely different systems with radically different design points. Minor changes though can have major ramifications on the final design, with their consequences

remaining hidden until late into the design process. For instance, a technology may be chosen from a range of alternatives because it is the cheapest option that can satisfy the stakeholders need. Assume, though, that the technology under consideration is at its upper performance peak of what it can deliver. Therefore, while this may be an acceptable technology choice at the beginning of the design process, a minor alteration to the stakeholder's need could render the selected technology incapable of performing the new need. Heavy penalties (both financial and scheduling) could then be incurred to redesign the system, as the technologies supporting systems may also need to be redesigned or replaced to meet this new need. Ensuring requirements are correct at the beginning of the design process is therefore vital if the system is to avoid redesign work.

Requirement elicitation occurs at the beginning of the design process when the knowledge and effects of these choices are most uncertain. In an ideal world the effects of these choices should be completely analysed but finite project resources and deadlines do not permit this. Nevertheless decisions have to be made, for the design to progress.

At the beginning of the design process the designer has the greatest freedom to make choices, yet the least knowledge about their consequences. [73] Initially the design space is completely open, full of possible solutions and no restrictions. This space however is too vast to optimise given the time and cost constraints placed on each project. To refine this region market analysis, research and trade studies are formed to define an area where acceptable designs may be found. Only solutions within this region are deemed acceptable while those which lie outside or deemed unacceptable. While a lot of effort is made ensuring this done correctly, the information used to make these choices could be uncertain or missing, unintentionally creating a design space that excludes the best solution.

Early decisions have two major effects. Firstly they affect future decisions. For instance suppose an aircraft design team decide to use turboprop engines on a new aircraft design. These engines however will need supporting systems to ensure they function correctly limiting the options which the designer can choose from. The other affect which has been highlighted by many authors and stems from this reduced freedom is the fact that early decisions commits future costs, with one author claiming it could be as much as 80% of the total overall cost. [74] Initial decisions are therefore the beginning of a snowball affect which highlights the importance of getting early decisions correct.

Figure 6 illustrates the usual trend of design knowledge, cost committed and designer freedom. As Figure 6 shows design knowledge and cost committed rise as the design progresses while the designer's freedom to make choices declines.

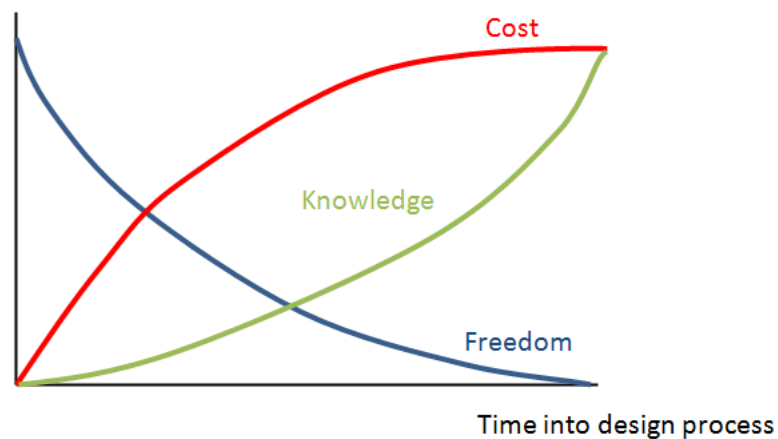


Figure 6 – Trend Of Design knowledge, Cost Committed And Designer Freedom [73]

In an ideal world stakeholder needs would not change. Stakeholder needs however can change and for many reasons throughout the design process. For example there is a new product from a competitor which would make their system redundant or the latest breakthrough technology did not mature as expected. To further complicate the matter changing needs are not necessarily converging on a particular point or even in a specific

direction but rather change depending upon the information emerging as the design progresses. Nevertheless the initial requirement is a good early representation of the stakeholder's need. For example an initial need for a system to transport 15 people is not suddenly going to change into a system that needs to transport 150 people, a change of transporting 12 to 20 people however is not beyond the realms of fantasy. System Engineering though cannot successfully manage these minor changes without incurring significant penalties in cost and time, especially if it occurs late in the design process. This lack of flexibility is seen as one of System Engineering greatest limitations.

Another limitation is the exit criterion. Using requirements as the sole exit criterion does in itself present its own problems. Firstly since requirements capture the needs of stakeholders, it is believed that only when all requirements have been met is the design acceptable. There are instances though when all requirements have been met and the design is unacceptable. Similarly there can be designs which do not meet all of the requirements but could potentially meet all of the stakeholder needs. While users of the System Engineering process would argue this problem is caused by poor requirement elicitation, which can be correct, it does highlight that requirement elicitation is not a perfect process. Nevertheless, the choices made during this process will be used to define what is acceptable and what is not, perhaps preventing the designer from selecting a superior design.

Secondly the focus of the designer shifts from providing the "best" overall system to the stakeholder to a design that meets all requirements. While meeting requirements is meant to achieve this goal, it only creates solutions that are acceptable. Designers are driven to find a solution which meets all of their given requirements. Once this has been achieved the design process can stop as their objectives have been met, even though this may not be the best overall solution for the system stakeholders. Designers can therefore fail to see the big

picture and are not forced to find a better solution if they have already found an acceptable design. In other words the process becomes more of a tick in the box exercise than truly concentrating on delivering the solution that stakeholders want.

Designing by requirements has one other major drawback, it does not provide designers with a method of choosing which design option is better or which design is better/best if multiple design solutions meet the list of requirement. It is unusual for only one design to be generated that is capable of meeting all of the elicited requirements; instead there are usually numerous designs that can. Take motor sport racing as an example. All cars need to meet the regulation requirements to race but all of the different teams have different designs with individual drivers having different racing setups. One of these designs however is superior to all the rest but system engineering is incapable of determining which one it would be. Designers try to resolve this issue with other design tools such as the Pugh matrix [75] but techniques such as this are highly subjective and explain why different design teams select different designs. Failing to provide an evaluation criterion to rank different designs is seen as a major weakness in the system engineering technique as all designs are assumed to be equally as good, but in reality this is not the case.

Do requirements represent the absolute minimum (or maximum depending on the aspect) the stakeholders are will to accept? If the answer is yes, then design teams are trying to find a solution that is just acceptable which may leave stakeholders disappointed, as this only the minimum acceptable not necessarily the best.

On the other hand if a percentage is added to force designers to seek better designs, the consequences of this may unnecessarily over engineer the solution ultimately driving up the cost of the solution or have undesired effects elsewhere. In either case the major difficulty still remains of forcing stakeholders to agree a definitive point between the acceptable and unacceptable, even before the design stages begin.

At present all stakeholder needs are defined by requirements within the System Engineering approach. If the needs of stakeholders could be defined without needing to be absolute, the limitations of requirements could be removed. One possible method of achieving this is to define the needs of stakeholders through fuzzy logic, which is discussed in the next section.

3.2.2 Fuzzy Logic

Fuzzy logic was first proposed by Professor Lotfi Zadeh in 1965 as a means mathematically represent partial truth, i.e. truth values between completely true and completely false. [76] Fuzzy logic is therefore a superset of the traditional Boolean Logic which can only define absolutes i.e. true or false. Although it is named fuzzy logic, the logic itself is not fuzzy but rather it describes and quantifies the fuzziness of things [77] and should not be confused with probability which predicts the likelihood of things occurring.

To capture this partial truth fuzzy logic applies a membership function to the data, usually ranging from zero to one depending upon the degree of truth within the statement. Like Boolean logic a zero value represents a false statement and complete non-membership to that state. Similarly a value of one represents a truth statement and complete membership to that state. [77] The values between zero and one however represent the degree of truth at that point.

To date the most common membership function has been triangular. A generic triangular fuzzy logic membership function is represented in Figure 7. Membership functions however can be any shape and do not need to be symmetrical as shown in Figure 8. While it is possible to have a square/rectangular shaped membership function as shown in Figure 9, this indicates that there is no partial truth within statement and is how Boolean Logic would be represented using a membership function.

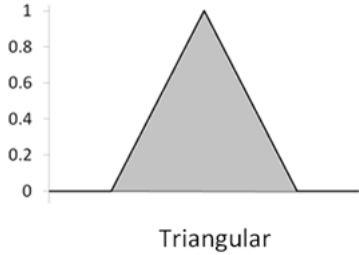


Figure 7 – A Triangular Fuzzy Logic Membership Function

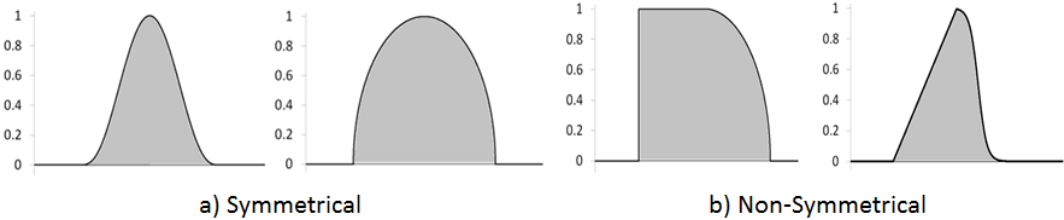


Figure 8 – Possible Fuzzy Logic Membership Functions

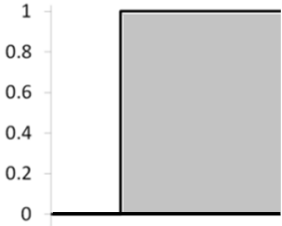


Figure 9 – Membership Function Of Boolean Logic

To illustrate the difference between Boolean logic and fuzzy logic consider Figure 10 which represents how both methods would define the thermal state of a room based on the room’s temperature.

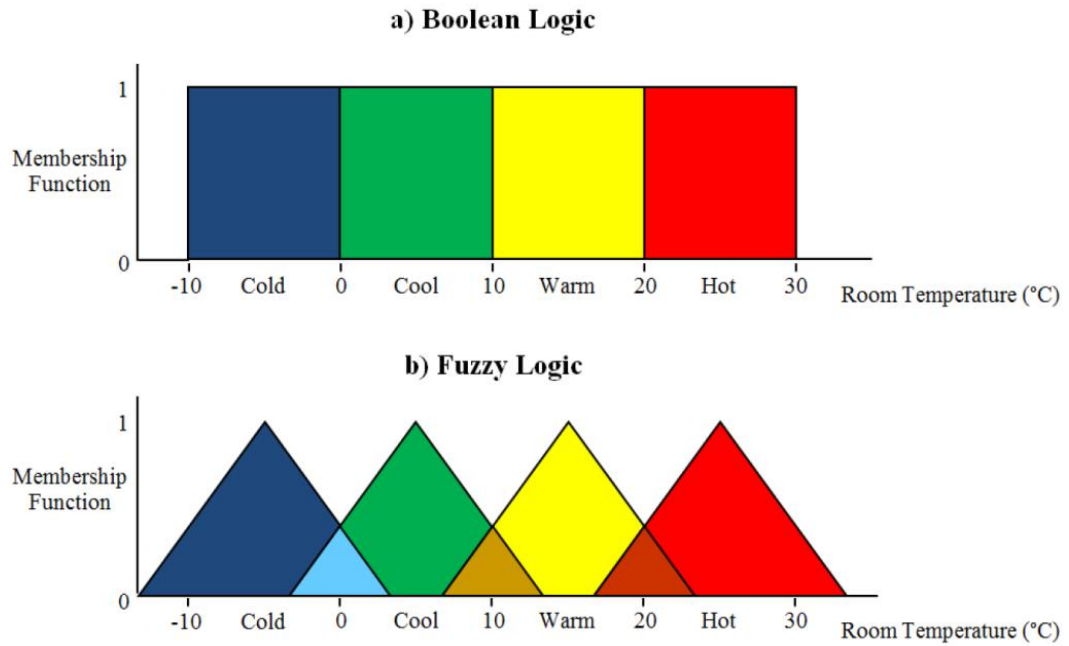


Figure 10 – Thermal State Of A Room Characterised By Boolean And Fuzzy Logic [78]

Boolean logic characterises things as absolutes i.e. completely true or completely false. To characterise the thermal state of a room using Boolean logic each thermal state must first be clearly defined. In this example the four thermal states (cold, cool, warm and hot) have been defined by a 10°C temperature range as indicated by Figure 10a. The thermal state of the room then corresponds to the category where the room temperature resides in Figure 10a. For example a room temperature of 17°C would indicate that the room was warm while a room temperature of 23°C would indicate that the room was hot. The thermal state of a room however is subjective and based on the person's perception. For example one person may find a room which is 21°C warm while another may find it rather cool. Characterising the thermal state of a room through Boolean logic assumes that each of the thermal states is mutually exclusive, divided by sharp boundaries. [77] This is not the case. In reality the transitions between these thermal states is gradual and overlapping rather than instant at a particular predefined temperature. Defining situations which are subjective (i.e. situations which include partial truths) should not be defined via Boolean logic, as it over simplifies and misrepresents the situation. Fuzzy logic however can capture

this gradual change as well as the multiple states due to its use of the membership function. Fuzzy logics ability to capture the partial truth within subjective situations is a major advantage over Boolean logic.

In design natural language or linguistic terms are often used to describe the wants and expectations of stakeholders at the beginning of the design process. Table 2 lists some of these common words and phrases. These words and phrases however are vague and subjective, making them unsuitable to base design decisions upon.

Table 2 – Common Subjective Needs From Stakeholders

Efficient	Lightweight	Low Cost
Fast	Easy to Use	Stylish
Reliable	Environmentally Friendly	Modern

None of these phrases fall into precisely defined membership categories but fuzzy logic can assist designers deal with these situations. Traditionally the above terms would be transformed into requirements (using Boolean logic) to remove their ambiguity. For example “Low Cost” is redefined as less than \$100 to purchase. Designs which are below \$100 are then considered to meet the “Low Cost” need of the stakeholders.

As demonstrated in the thermal state example above, defining needs in this way can misrepresent the needs of the stakeholder. In traditional techniques it is assumed that all boundaries are hard and inelastic. In reality this is not the case as some if not most boundaries are elastic to some degree. While less than \$100 has been defined as “Low Cost”, no stakeholder would argue that comparatively a design priced at \$102 is expensive but rather “Low Cost” to a lesser degree. In the System Engineering process, the \$102 design is rejected as it doesn’t meet the above requirement of being less than \$100.

3.2.3 Capturing Stakeholder Need Within New Design Process

This research proposes that both Boolean logic and fuzzy logic should be applied to capture stakeholder needs within the new design process. In instances where a need has a clear and definitive boundary between acceptable and unacceptable, Boolean logic should be applied otherwise fuzzy logic should be employed to capture the need. Needs captured using Boolean logic will be known as requirements within the new design process while needs captured through fuzzy logic will be known as desirements. Requirements in the new design process will therefore function exactly the same way as requirements do within the system engineering process, i.e. what the system must do to be acceptable. Desirements on the other hand will define needs but instead of a definitive point defining between acceptable or not, a range of values with a varying degree of acceptability will be used. Examples of needs defined by requirements include the system must meet all regulations or if the system is to become the best at something i.e. the fastest road production car. Examples of needs defined by desirements include any need that does not have a definitive boundary between acceptable and unacceptable, such as those listed in Table 2.

Figure 11 illustrates the difference between capturing a need through Boolean and fuzzy logic.

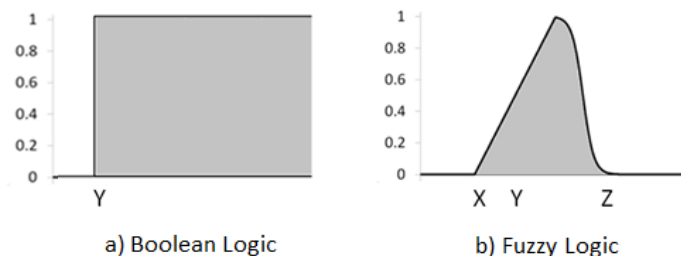


Figure 11 – Comparison Of Need Captured Through Boolean And Fuzzy Logic

In Figure 11 an acceptable solution may be found within the grey shaded region with Point Y representing the same position on each diagram. A membership function of zero indicates

that the design is unacceptable while a membership function greater than zero indicates an acceptable design. The closer the membership value is to one (the maximum membership value) the more desirable the design is to the stakeholders.

As expected Figure 11a which represents a need captured via Boolean logic (i.e. a requirement) clearly indicates that an acceptable solution may be found anywhere right of the point Y. Figure 11b which represents the need captured by fuzzy logic (i.e. a desirement) however provides designers with more useful information, information which could not be captured by using Boolean logic. In Boolean logic it is assumed all points are equal to the right of Point Y. This is not the case. Boolean logic only defines the acceptable and nonacceptable regions whereas fuzzy logic can also capture the desire of stakeholders; informing designers on how to improve the design i.e. move towards the value which corresponds to a membership function of one.

Another benefit of using fuzzy logic to capture a need that doesn't have a definitive boundary between acceptable and unacceptable is that it allows designers to make better choices on the stakeholder's behalf. For example stakeholders want a fast car. Defining this need as a requirement would result in statement such as:

"The car must be capable of travelling of at least 210 km/hr under normal operating conditions".

A requirement forces designers to deliver a car capable of travelling of at least 210 km/hr, regardless of how delivering this value affects the design. Fuzzy logic and its use of a membership function however can provide designers with the acceptable "wobble" room around this need, leading to better choices while still prefiling stakeholder needs. For instance 200 km/hr would still satisfy the stakeholder need of a fast car but achieving this value (200 km/hr) compared to the original value (210 km/hr) creates a 10% saving in costs.

This trade may be very advantageous to stakeholders but is not considered if all needs are defined by requirements.

A further advantage of using fuzzy logic over Boolean logic is that it manages stakeholder expectations much better as the membership function can be closed at one or both ends. In design it is important for everyone to understand what the designed system must do but it is equally important to understand what the system will not do if it is to avoid stakeholder disappointment and be a success. In Figure 11a everything to the right of Point Y is acceptable, even if it is not possible to reach that region. Not all stakeholders know what is feasible and may lead to disappointment when the system created meets the requirement but not their expectation. Closing the membership function (i.e. returning the membership function to zero) therefore not only bounds the membership function but also the stakeholder's expectation before the design team begin generating concepts. Bounding expectations clearly defines the system's place within the market and is therefore less likely to be subject to change requests due to competitor information emerging throughout the design process.

Defining the needs of stakeholders via fuzzy logic can also assist in the negotiation stage as it can communicate the preference of stakeholders much better than Boolean logic. For example if the preference of a stakeholder is captured using Boolean logic, their preference is reduced to a single point which defines what is and what is not acceptable from that stakeholder. These points however are likely to be different for each stakeholder meaning everyone is in disagreement before the negotiation stage begins. This is normal. While points close to one another may indicate partial agreement, it does not provide stakeholders with any information about their flexibility around this preference. Fuzzy logic however can as Figure 12 determinations.

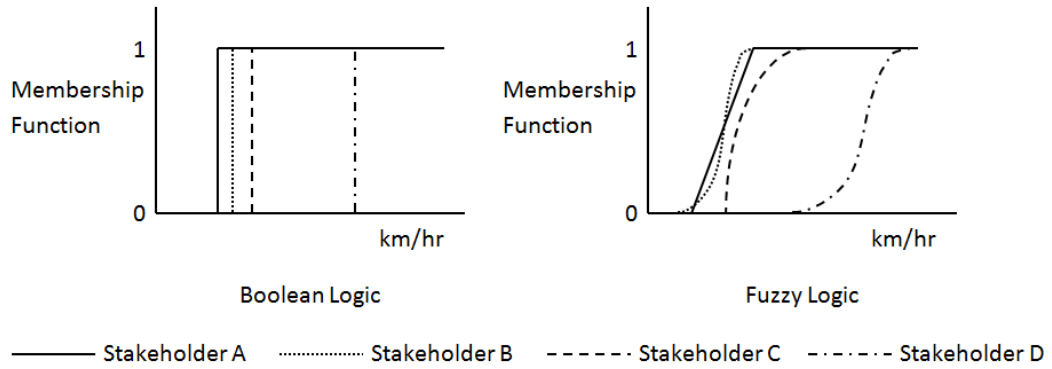


Figure 12 – Stakeholder Speed Preference

Figure 12 compares the speed preference of four different stakeholders, A, B, C and D defined by Boolean and fuzzy logic. From Figure 12a, no one is in agreement as all four stakeholders have a different preference. Figure 12b however indicates that stakeholders A and B are almost in agreement as their membership functions are comparable. Stakeholder C on the other hand mostly agrees with stakeholders A and B while stakeholder D is far from agreement. Knowing this information the designer can request further reasoning from all four stakeholders about their choice so it can be shared during the negotiation stage. Having this information available not only avoids delays, it also provides a good starting point to start for the negotiation.

Defining stakeholder needs through fuzzy logic also changes the dynamics of the negotiation. If requirements are used, the need is transformed into a clear target, differentiating between what would be considered acceptable or not. While this seems a simple task, acquiring agreement between multiple stakeholders who have different preferences on what this target should be is difficult, as ultimately some if not all stakeholders have to compromise to reach agreement, leaving most aggrieved. While the design team can assist in this process by providing typical or assumed cause and effect information, the information presented to stakeholders is often uncertain yet stakeholders are forced to make a choice. Using fuzzy logic however allows the negotiation to conclude

without the necessity to have a precise target but instead have a range with a preference for the design team to work towards. This avoids stakeholders being forced to their needs to absolutes, allowing the design team to make the best possible trade-off on their behalf when more accurate information is available. Additionally since the preference of all stakeholders is included, no stakeholder will feel their preference has been ignored but rather they have contributed to the agreement. Once an agreement has been reached between all stakeholders the system preference can be created. An example of this is illustrated in Figure 13 which is derived from the information displayed in Figure 12 and the negotiations held between the four stakeholders.

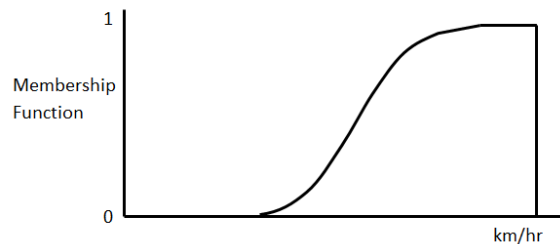


Figure 13 – System Speed Preference Defined By Fuzzy Logic

These membership functions will be known as the desirability functions within the new technique as they are the desires of the stakeholders. Defining needs like this however affects the design space in which the design team may operate. Figure 14 for example compares the solution space created through Boolean and fuzzy logic with the shaded region indicating the area where an acceptable solution may be found.

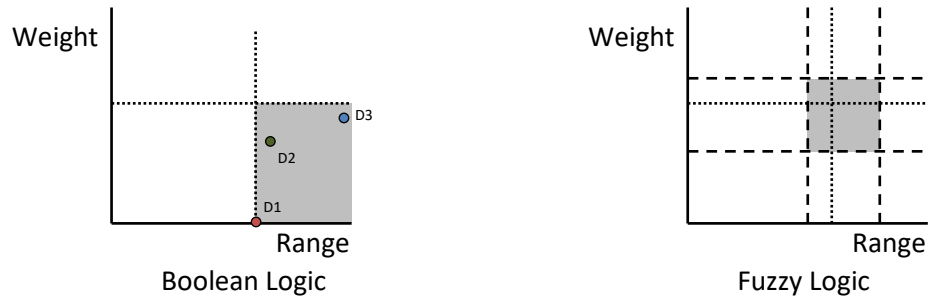


Figure 14 – Acceptable Solution Space Defined By Boolean And Fuzzy Logic

From Figure 14, it is clear that the solution space created by Boolean logic is larger than the solution space created by fuzzy logic. While a larger solution space is advantageous as it has the potential to obtain more acceptable solutions, the solution space created by fuzzy logic will be more densely populated with solutions that are feasible and met the true needs of stakeholders compared to Boolean logic. Take for example design point one (D1) where the design meets the desired range but weighs zero, although this design is acceptable it is nevertheless unachievable. Additionally while design point 2 and 3 (D2 and D3 respectively) are both acceptable and achievable designs they could both be beyond the need of the stakeholders, affecting other design aspects not shown in Figure 14 such as the designs costs or emissions.

Creating a solution space using a fuzzy logic also has one other noticeable difference compared to using only Boolean logic. The solution space created by Boolean logic is rigid whereas the solution space created by fuzzy logic is non-rigid. If only Boolean logic is used the solution space must be defined definitively and correctly at the start of the design process, an almost impossible task especially when designing a complex system, to ensure the best solution resides within its boundaries. The benefit of using fuzzy logic is the solution space is allowed to expand or contract avoiding the scenario where the best is not within its bounds.

3.3 The Role Of An Objective Function Within The Design Process

From the review of the current state of the art methodologies, it became clear that being able to differentiate between designs and state which design is best is very advantageous within a design process. To achieve this, an objective function will be used within the new design process. This section will focus on how these functions are developed, what effects they have upon the selection process, how they are used and how they have progressed within the engineering community; explicitly the Multi-Disciplinary Optimisation (MDO), Multi-Objective Optimisation (MOO) and finally the recent Value Driven Design objective functions. Throughout this discussion the aim is to review each of these techniques with the overall goal of providing designers with a method of developing the correct objective function which will allow them to confidently make the correct decisions on behalf of the stakeholders throughout the design process.

3.3.1 Objective Function Introduction

The most simplest and complete definition of an objection function is an equation that has to be maximised or minimised given certain constraints and variables. [79] An objection function is usually a result of a business goal expressed in a mathematical form to aid in the decision making process. In the context of system design, an objective function is used to evaluate various design options according to the desires of the stakeholders. The objective function objectively scores each design option allowing the various designs to be compared and ranked. It is therefore important that this function is constructed correctly and representative of the stakeholders desires to ensure the best design option is chosen. Design variables and constraints are two important elements with an objective function and will now be defined for clarification.

Design Variable: These parameters are independent and controllable by the designer. While they vary depending upon the design problem, typical design variables include component dimensions and material choices.

Design Constraints: These are restrictions placed on the design. They can come in many forms and from many sources. All constraints must be met as violating only one can make the design unacceptable.

The generic form of an objective function which must be minimised is shown below in Equation 3. [80] If however the “Minimise” expression is replaced with “Maximise” it would represent the generic form of an objective function which must be maximised.

$$\begin{aligned} &\text{Minimise} && f(x) \\ &\text{Subject to} && f_i(x) \leq 0; \quad i = 1, 2, \dots, m \\ &&& f_j(x) = 0; \quad j = 1, 2, \dots, n \end{aligned} \quad (3)$$

Where $f(x)$ is the objective function, x is the set of design variables and $f_i(x)$ and $f_j(x)$ representing the constraints of the design problem.

3.3.2 Design Optimisation

Today optimisation is a given feature within any design environment as without it there is little chance or no motivation for the design team to create the best product for the stakeholders. When first introduced in 1940's the technique was more commonly known as mathematical programming, [81] with most problems being defined by linear equations. Today's optimisation problems are usually more complex and non-linear in nature. Optimisation (as described by the Merriam-Webster dictionary [82]) is the

“act, process, or methodology of making something (as a design, system, or decision) as fully perfect, functional, or effective as possible; specifically: the mathematical procedures (as finding the maximum of a function) involved in this”.

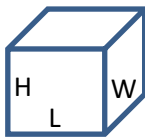
In more simple terms however it is process which maximises or minimises an objective function within given certain constraints. Below is a simplified example of designing a box with two constraints to demonstrate the principle.

Design Problem

A design team has been asked to create a box for a delivery company where the box minimum volume must be 100 m^3 . For the design to be accepted, the base of the box must be square and be made from the minimum amount of material, assuming no wastage.

Design Solution

As the goal of the design problem is to minimise the amount of material required to make the box, the surface area of the box must be minimised. Additionally by applying the above information, Equation 4 defines the problem needing solved, with L, W and H defining the boxes length, width and height respectively.



$$\begin{array}{ll}
 \text{Minimise} & \text{Surface Area} = 2LW + 2LH + 2HW \\
 \text{Subject to} & \text{Volume} = HLW = 100\text{m}^3 \\
 & W = L
 \end{array} \quad (4)$$

Using substitution and rearrangement the minimum surface area of this box is found when the box is a cube i.e. when all sides are equal. To minimise the surface volume and meet the constant, the length of each side should therefore be 4.64 m which creates a box with a surface area of 129.27 m^2 . Although this problem is simplified for demonstration purposes, the approach can equally be applied to more complex design scenarios.

Optimisation has become an important process within industry with many businesses applying the technique on both large and small scale. The purpose depends upon the need of the business but typical examples include maximising profit or minimising waste. Within the aviation sector, the process is commonly referred to as design optimisation with the

goals of the technique usually falling within three broad categories; maximising performance, minimising weight or minimising costs as past programs have shown [83] [84] [85] [86] [87] [88]. Design optimisation however can be applied to any customer specific goal or goals. [89]

Traditionally, the aviation industry has employed the System Engineering technique when developing complex systems which is a requirement based process. As the requirements are flowed down from system to component level; each subsystem/component is also assigned its own unique objectives, constraints and variables based on the objectives, constraints and variables of the above level. As each level is interlinked with variables from one level feeding into other, the optimisation process becomes iterative, possibly requiring a large number of iterations to find an acceptable solution, assuming one exists. Iterations however can be expensive in terms resources i.e. finance, time and personnel especially as the number of system levels and the complexity of the system increases.

Furthermore optimisation in aircraft design is usually split into subsystems (wing, fuselage, engine, etc) or disciplines (structural, aerodynamics, propulsion, etc) where specific design groups are given charge of optimising their own particular design problem by allowing them to make all relevant design decisions. While in theory this appears to be a good decision as each subsystem is optimised, in reality the technique isolates and decouples designers from the task in hand. This isolation and decoupling causes designers to become focused on optimising their own design and not the overall system; leading to sub-optimal systems being created. To correct this Multi-Disciplinary Optimisation and Multi-Objective Optimisation has emerged.

3.3.2.1 Multi-Disciplinary Optimisation

Multi-Disciplinary Optimisation (MDO) first emerged in the 1980's [34] as a solution to structural problems being encountered within aerospace industry. While the optimisation

technique is similar to the traditional design optimisation discussed in the previous section, MDO is considered a superior method of optimisation as it considers the interaction and the various trade-offs between different disciplines and subsystems when searching for the optimum solution. In traditional design optimisation, the optimisation process is sequential with teams focused on optimising their own part of the design. Once a design team/discipline has completed their optimisation it is then passed to another where they too complete their own optimisation task. This process continues until all teams/disciplines have optimised the design. In aircraft design for example the traditional design optimisation process may begin with the aerodynamic team. Once the aerodynamic team have finished their optimisation, the design is passed to the structural team, who then optimise the structure of the aircraft (given this shape) before passing it to another team. MDO however combines the needs of multiple disciplines (aerodynamics, structures, propulsion, controls, etc) into one function, allowing simultaneous optimisation of the design problem [90] [91] [92] [93] [94] rather than it occurring in isolation. Performing the optimisation in this manner has the ability to reduce cost and time overruns due to the needs of various disciplines being considered concurrently [90] while additional information is provided earlier about the final design because of multiple disciplines working together.

Today the MDO process is common within many industries including automotive design and electronics but it is the aerospace sector where the approach remains the most popular with it being implemented across a wide range of applications for aircraft design including the Boeing Blended Wing Body concept [95] [96].

Implementing MDO however does come with some disadvantages which may explain why this process is not preferred by all engineers. For instance, increasing the number of disciplines involved within the design process increases the complexity of the problem, making the optimisation procedure more difficult to solve and more resource intense [90]

[97]. Additionally as the overall objective function is decomposed for each discipline, creating unique and local functions, the optimisation process returns to design teams optimising in isolation, concerned with only their function. This may cause design teams working at local level to forget to consider how their decisions affect the overall system, limiting the effectiveness of MDO approach. [90] [97]

As an optimisation method, it is clear that the MDO approach is superior method to the traditional design optimisation. Its ability to consider the needs of multiple disciplines concurrently is certainly one of the reasons the approach has become so popular. The technique however does have its limitations with its ability to find an optimal solution ever more challenging as the level of complexity increases.

3.3.2.2 Multi-Objective Optimisation

Multi-objective optimisation (MOO), also known as multi-attribute optimisation (MAO) is the process of mathematically optimising more than one objective simultaneously. [98] For example an airliner may wish to minimise the cost and weight of each seat on their aircraft while maximising the comfort for its passengers. Each of these attributes will have its own objective function, all of which will be optimised at the same. In cases such as this where the objectives are conflicting it is rare that all objective functions will be optimised at the same design point; creating a compromised solution. For instance the seat design which offers maximum comfort to passengers is unlikely to also possess attributes such as lowest cost and weight. Unlike single-objective optimisation, there is no single optimal solution. Instead there are usually multiple solutions which are non-dominated or non-inferior due to the interactions between the different objectives. These types of solutions are commonly known as Pareto-optimal solutions. When the utopia point (a point which all objective functions are optimised) cannot be achieved, the MOO approach searches for solution which has the minimum vector distance from the utopia point. [99]

The basic formulation of MOO is provided in Equation 5 [98] [99]

$$\begin{aligned}
 &\text{Minimise} && F(x) = [f_1(x), f_2(x), f_3(x), \dots, f_k(x)]^T \\
 &\text{Subject to} && g_i(x) \leq 0; \quad i = 1, 2, \dots, m \\
 &&& h_j(x) = 0; \quad j = 1, 2, \dots, n
 \end{aligned} \tag{5}$$

Where $F(x)$ is vector containing multiple objectives, x the design variable or chosen attribute, k the number of objectives functions to be considered with $g_i(x)$ and $h_j(x)$ representing the constraints placed on the design problem.

MOO approaches can be categorised into four main groups depending upon the selection process used to select the optimum solution. The four methods include 1) no preference 2) priori methods 3) posteriori methods and 4) interaction methods; each of which is will now be discussed. [98] [100]

- 1) No Preference Method – In this case the preference of the decision maker is not required throughout the solving of the problem. If the decision maker is unable to express what they want from a particular design the no preference method approach is used.
- 2) Priori Method – In this method the preference of the decision maker is known before the search begins. The selected solution will be one which satisfies these preferences.
- 3) Posteriori Method – In this method the preference of decision maker is delayed until presented with a range of solutions. Once presented with this range of solutions the task of the decision maker is to review them and then select one as the chosen solution.
- 4) Interactive Method – This method may be considered a combination or blend of the priori and posteriori methods already discussed with the decision maker playing a more active role throughout the complete process. After each iteration the

results are used to update the preference of the decision maker with the process continuing until the decision maker is satisfied with a solution.

Similar to the MDO approach, there are both advantages and limitations of employing MOO. A major benefit of using MOO is its ability to consider multiple, often conflicting, goals/objectives concurrently allowing better trade-offs to occur when making a decision; compared to optimising a single attribute. [101] The MOO process can also capture the decision maker's preference between these objectives which can assist in the selection of the optimum solution [98].

One of the main concerns with the MOO approach is its repeatability. While the preference of the decision maker may be captured, this preference is not constant; as different people may view or categorise these objectives differently. This makes the process virtually impossible to repeat and obtain the same solution if performed by different people. Secondly but continuing on from the first point, if there is only one decision maker the decision may be biased favouring particular aspects.

3.3.3 The influence An Objective Function Has On The Chosen Solution

Objective functions are common tools used within engineering to optimise a design. Since they assist designers make decisions it is important that they are formulated correctly to enable the optimum solution to be selected; a point highlighted in studies conducted by Collopy [67] and Price et al. [86].

Collopy's [67] optimisation study of an aircraft propulsion system for example highlighted how different objective functions influence the chosen solution. The aim of this study was to determine the optimum bypass ratio of the engine. Within the study, the design problem was repeated using three different economic functions namely operator profit, the direct operating cost and surplus value. The results of this study can be seen graphically in Figure

15 where the red dot on each graph indicates the optimum and therefore select point according to that objective function.

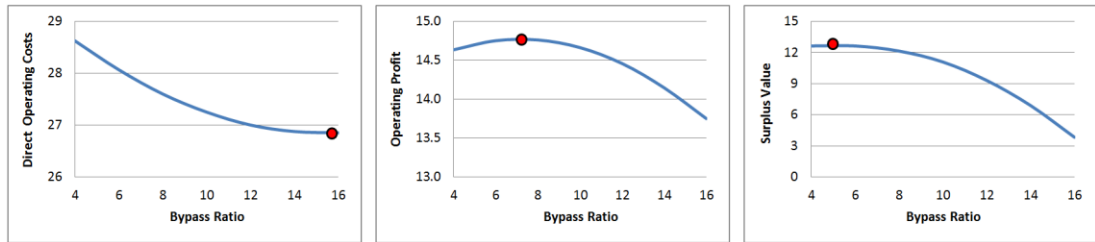


Figure 15 – How The Objective Function Alters The Selected Design [67]

From Figure 15, it is clear that each objective function creates a unique optimum point. If the objective is to minimise the direct operating costs of the design the engine should have a bypass ratio of 15.7. Similarly if the objective is to maximise operating profits or surplus value the engine should have a bypass ratio of 7.2 and 5.0 respectively. Although Collopy's study is greatly simplified as it only considered varying one variable i.e. the bypass ratio of the engine, it does demonstrate the influence objective functions have on the chosen design and the necessity for the function to be correct, to enable the optimal system to be chosen.

Creating an objective function which only focuses on one design phase however can also prevent the optimal solution from being selected. An aircraft manufacturer for instance may construct a new aircraft using conventional metallic materials (e.g. Aluminium 2024) or the latest advanced composites (e.g. carbon fibre). If the decision was based on purely on the cost of manufacture, the conventional metallic material would be the obvious choice as Aluminium 2024 is significantly cheaper to buy [102] and manufacture than carbon fibre. If however the designer factors in other phases such as operations and maintenance, the choice becomes less obvious. While the upfront costs associated with using carbon fibre are undesirable, selecting carbon fibre does extend the time between maintenance periods, [103] increasing the utilisation of the aircraft. Additionally it may be possible to reduce the

weight of the aircraft using components made from carbon fibre compared to manufacturing them out of Aluminium 2024 which may create significant long term saving (especially in the operation phase) when the complete life cycle is considered. Not considering the complete life cycle of the system therefore can lead to poor choices and/or trades overall, preventing the true optimal solution from being selected. While this ultimately increases the complexity of the decision, both this material selection example and Collopy's study stress the need that a suitable objective function be created to allow the designer to make the best and fully informed decision; otherwise a suboptimal solution will unintentionally be selected. The optimisation process therefore must include all relevant attributes within its evaluation criteria if it is to deliver the true optimal solution.

To achieve this aim, the aerospace community have been investigating using a system level value function to optimise their designs. [56] [66] [67] [68] [69] [88] [104] [105] [106] [107] Unlike objective functions based on specific attributes such as weight and cost, a value function has the ability to combine multiple attributes into a single function; allowing the designer to assess multiple aspects at the same time. This encourages designers to seek the optimal system rather than a design that is optimal on one particular attribute. Additionally by employing the value function at system level rather than at subsystem or component level, the optimisation process becomes unified; with all designs teams working towards one common goal. It was for these reasons the decision was made to employ a system level or overarching value function within the new design methodology.

In studies [56] [66] [67] [68] [69] [88] [104] [105] [106] [107] the value functions were all employed using the Value Driven Design technique. Value functions, however, can be employed in any technique and are not limited to just the VDD approach. For instance it is possible to use value functions in traditional System Engineering but in doing so the role of the function changes. In VDD, the value function drives the design as the process seeks to

maximise value rather than fulfil requirements. In SE the value function is used to assist the designer differentiate between acceptable designs but it constrained to the solution space defined by the requirements.

The concept of value and its definition is discussed in more detail in the next chapter.

3.3.4 Need For An Improved Objective Function

Objective functions are common tools used within engineering to optimise a design. To optimise a design a designer has two options, use a single objective function or employ multiple objective functions. Regardless of what option is chosen developing a suitable objective function(s) is still a difficult task; as the designer must first decide what attributes to include (or excluded) from the evaluation criteria. Objective functions in the past have traditionally be been based on a particular requirement(s) with minimum weight or minimum operating costs representing typical objective functions employed within the aviation industry. People however rarely evaluate designs based on a single attribute but rather on a range of attributes. For example as well as minimum operating costs, people may also include build quality, system performance, reliability etc within their evaluation criteria. Optimising a design using a single attribute such as weight or cost is therefore not enough.

Many of the objective functions used today however typically only consider one stakeholder, one aspect of the design and/or one design phase. In aircraft design for example there have been numerous studies conducted which have been optimised using a direct operating cost function. These functions however only capture one of the concerns from one stakeholder, i.e. the airline operator as their primarily focus is on the economic aspect of the design during the operation phase; commonly ignoring other aspects, design phases and stakeholders.

In an attempt to overcome this problem, studies by Antoine [108] and Kroo [109] as well as their collaboration work [110] [111] proposed using a multi-objective optimisation approach to allow the concerns of multiple stakeholders to be incorporated within the decision making process. The focus of these studies was to create a more environmentally friendly aircraft.

By quantifying the relationship between aircraft design, operating costs and aircraft emissions, it was possible to have trade-offs between the two. While this is an improvement, the usefulness of this analysis is limited; as it fails to consider the impact these choices have on other stakeholders or design phases.

As an alternative to using direct operating costs, Markish [112] investigated the prospect of using a value metric to design an aircraft. In this study, value was considered only from the perspective of the manufacture and although the tool incorporated various models including performance models, manufacturing and development cost models, revenue models and market demand models it too was limited by what it included. Markish acknowledged this point and stressed that it would be a “recipe for disaster to ignore the value to other stakeholders”. [112] Nevertheless this work did demonstrate the benefits of using a value metric.

To overcome this limitation a new objective function has emerged and is seen by its creators as the best solution to overcome the problems listed above. The objective function uses a metric known as surplus value, which in essence is the sum of differences between the revenue and cost of each stakeholder. Equation 6 represents this statement mathematically where V_s is surplus value of the system, R_{sj} revenue generated of each stakeholder, C_{sj} costs incurred by each stakeholder and n the number of system stakeholders.

$$V_S = \sum_{i=1}^n (R_{si} - C_{si}) \quad (6)$$

Whereas Markish's tool only considered one stakeholder, surplus value has the ability to consider multiple stakeholders simultaneously. By including the revenue potential and costs of each stakeholder within a single all-encompassing objective function, the design team can quickly assess their options and determine how their decisions not only affect the system's value but also individual stakeholders. Surplus value is of course a purely economic measure which is easily understood i.e. the higher the surplus value, the better the design is for the system stakeholders. Its ability however to combine important aspects such as profit generation, operating and disposal costs into one function allows designers to easily make decision which consider these aspects rather than on solely traditional performance measures of design features versus cost.

The term surplus value was first introduced by Pierre-Joseph Proudhon [113] but it was the German philosopher and social scientist Karl Marx who greatly developed the theory [114]. Karl Marx is most renowned for his theories in economics with his works becoming the foundation for many of today's economic thoughts. When working on his concept of surplus value, Marx was fighting on the side of proletarians (labours, typically industrial workers) as he believed in the ideology of socialism. Through his work he demonstrated that the labours work did have value to their employers, which contributed to the businesses profits. The following simplified example can be used to illustrate Marx's theory of surplus value in the most basic form. Imagine an employee who has an hourly wage of \$30. During this hour the employee is able to transform the raw materials provided, into a product worth \$150, for instance creating a beautifully crafted table from timber strips. After deducting the incurred expenses during the time e.g. cost of original raw materials, utility costs, equipment depreciation etc. of \$70 an hour, the employer receives a surplus of

\$50, as the total expense is \$100 an hour (labour at \$30 and expenses at \$70) but the product is worth \$150. The difference between the revenue and cost is known as the surplus value. This demonstrates that surplus value is gained if the labours produce more value than they cost the employer. Similarly the reverse is true where surplus value is lost if value created by the labours is less than the cost to the employer. This simple example also illustrates that profit can be increased if the costs are reduced.

Marx's theory of surplus value changed the belief/thinking of both employees and their employers and continues to influence the thinking of many people today. One of major advantages of using surplus value is that it considers the views or concerns of all stakeholders when making a decision not just a limited few in isolation as previous design studies have done. This is clearly highlighted when earlier works by Markish and Wilcox [115] [116] are compared with designs generated using surplus value. In their works [115] [116] sizing and configuration tools are used to considered the aircraft's performance whereas the economics of the aircraft are considered through separate revenue, development and manufacturing cost models. After analysing their work however their method really only considers the costs to manufacture, virtually ignoring other stakeholders. Surplus value on the other hand combines the cash flow of all stakeholders into one function allowing the effects of various decisions on all stakeholders to be taken into consideration. In doing this surplus value can be described as a single all-encompassing objective function which encourages designers to seek the best design for all stakeholders rather than a single stakeholder or discipline. It is because of this that objective functions developed from the theory of surplus value have used within the Value Driven Design approach.

3.3.5 Surplus Value Development

As many studies within the Value Driven Design field have focused their attention on utilising surplus value; a review of the most relevant works will now be performed. Before this is done however it is important to note that up until now these studies have concentrated on developing functions for systems within the aerospace industry; it is therefore unsurprising that the attributes included within these functions relate to aircraft design.

The most commonly accepted form of surplus value equation is:

$$V_s = P_R - C_{Man} \quad (7)$$

where V_s is the systems surplus value, P_R is its reservation price and C_{Man} the costs incurred, specifically manufacturing costs. Equation 7 is therefore very similar to Marx's definition of surplus value with the exception that the final value has been substituted with reservation price and costs incurred being the expenditures for the manufacture or producer.

Using Equation 7, the surplus value of a system is defined as its reservation price minus all costs, where the reservation price is defined as "the maximum price any customer is willing to pay in the absence of competition". [69] Since surplus value ignores competition, it can therefore be seen as a simplified form of profit which would consider market forces.

Although Equation 7 may seem to be an overly simple objective function to compare various designs concepts with, it has become the foundation for many of the surplus value equations developed within VDD. This includes most noticeably the equation developed by Castagne et al. [66] which was later developed further by Cheung et al. [56]

In Castagne et al. study [66] Equation 7 was altered and tailored towards profit; where π is profit, R the airline revenue, DOC the direct operating costs, r the airline discount rate, MC the manufacturing costs and SV_2 the surplus value of another competing aircraft.

$$\pi = \sum_i^{\text{Aircraft Life}} [(R - \text{DOC})(1+r)^{-i}] - MC - SV_2 \quad (8)$$

In Castagne et al. study the newly formed Equation 8 was used to compare and rank the design of two different aircraft fuselage panels. If the surplus value of one aircraft was to be determined, Equation 8 can also be used with the final term (SV_2) removed. Although this equation is an enhancement over Equation 7 as it provides designers with more information and insight from their choices it still has its deficiencies. For instance, only the direct operating costs and manufacturing costs are considered, ignoring other significant costs such as research and development (R&D) or environmental costs. To correct this and allow Value Driven Design to accomplish its vision of providing design teams with more insight and information on their choices as early as possible within the design stage. Cheung et al. [56] proposed the following surplus value equation i.e. Equation 9.

$$V_s = r_p N_{a/c} [r_c F_y (R_{P\&C} - C_{OP} - C_{D\&C} - C_E) - C_M] - C_D \quad (9)$$

Where V_s is surplus value, r_p the discount multiplier based on a single year's revenue and costs for the manufacture, $N_{a/c}$ the total number of aircraft to be produced, r_c the discount multiplier based on a single year's revenue and costs for the customer, F_y the aircraft's annual utilisation, $R_{P\&C}$ the total airline revenue (for all flights and for both passengers and cargo), C_{OP} the aircraft's total operating cost (both direct and indirect), $C_{D\&C}$ the costs associated with flight delay and cancellation, C_E the externality costs (which is a representation of societal good, currently the costs associated with aircraft noise and

emissions), C_M the aircraft's manufacturing costs and C_D the aircrafts research and development costs.

By including these additional revenue streams and costs within their equation Cheung et al. [56] has been able to significantly improve the original surplus value Equation 7; as it captures nearly all of the key economic components within aircraft design allowing designers to better understand the effect of choosing different options not only have on other stakeholders but throughout the various design stages. For instance, manufactures could use Equation 9 to determine what effect a change in material may have on other stakeholders such as society, airline profits and maintenance crews. There however is one most noticeable absentee in their equation, the systems disposal costs. The disposal costs of system are very important as they can easily diminish any profits made earlier in the systems lifecycle. For example the incorporation of advanced composites within aircraft design has been steadily growing over the past few decades due to their many benefits over traditional metals; such as weight reduction and extended maintenance intervals. The cost of producing these new composite components however differs from the traditional metals components due to the price variation in both the raw materials and manufacturing processes employed during their creation. It is therefore not unreasonable to assume, due to the current lack of data, that the cost of disposing these new components would also be different and may outweigh the envisaged cost saving of using advanced composite materials. It is therefore important that the disposal costs are incorporated within the surplus value equation to ensure that all system stakeholders and their concerns are included within the all-encompassing objective function required by VDD. To achieve this Mullan [70] altered Equation 9 to incorporate the disposal costs and is shown in Equation 10.

$$V_s = r_p N_{a/c} \left[r_c F_y (R_{P\&C} - C_{OP} - C_{D\&C} - C_E) - C_M - C_{Disp} \right] - C_D \quad (10)$$

Equation 10 is the currently the most up to date form of the surplus value equation and for the purpose of this research, all studies evaluated using surplus value will be determined via this equation. As some of the terms within this equation may be unfamiliar to some readers, the next section briefly outlines the definition of each component.

3.3.5.1 The Surplus Value Equation

As mentioned in the previous section, Equation 10 is currently the most complete surplus value equation defined by the VDD community for aircraft design. By accounting for all possible revenue streams and costs throughout the systems lifecycle, the equation is able to calculate the potential economic value of any prospective design. As can be seen, the equation has eleven key elements. These are: the producers discount multiplier, number of aircraft produced, customer discount multiplier, annual utilisation of each aircraft, revenue generated per flight, total operating costs per flight, delay and cancellation costs per flight, externality costs per flight, manufacturing costs per aircraft, disposal costs per aircraft and total development costs. A brief description of each of these key elements is provided below. For more information please refer to Ref. [56], [68], [105] and [106].

Producer (r_p) and customer discount multipliers (r_c)

Both the producer (manufacture) and customer (airline) discount multipliers are functions used to discount all of the future cash flows to their present day value. A more detailed definition can be found in Sutcliffe and Hollingsworth [64] where they define these factors as “multipliers on future revenue and costs that are dictated by the producer and customers discount rates and program investment horizons”. To calculate these multipliers Equation 11 is used where “ σ ” represents the discount rate given to each stakeholder and “ t ” the program duration (in years) of each stakeholder.

$$r = \frac{1}{\sigma} - \frac{1}{\sigma(1+\sigma)^t} \quad (11)$$

Total number of aircraft produced ($N_{a/c}$)

This term refers to the expected number of aircraft to be produced including those manufactured during the research and development phase.

Annual Utilisation (F_v)

The annual utilisation of an aircraft is the estimated number of hours per year the aircraft is expected to be operational and is therefore dependant on aircraft type and flight range. The annual utilisation of an aircraft is defined by the customer (i.e. the airliner) but if the actual data is unknown Liebeck [117] provides representative data for the number of trips taken per year for short, medium and long range flights. This information is summarised in Table 3.

Table 3 – Representative Number Of Trips Per Year Depending Upon Flight Range [117]

Range	Trips per year
Short	2100
Medium	625
Long	480

Revenue per flight ($R_{P\&C}$)

This is the total income received by the airline for operating a particular flight i.e. the money received from both passengers and cargo. There are a range of factors which can effect this term but is highly dependent on flight distance and customer demand. Sutcliffe and Hollingsworth [64] have provided equation 9 as a means to calculate the total revenue generated per flight. This is shown as Equation 12 below.

$$R_{P\&C} = (\text{Seats}_{\text{Available}})(LF_{\text{Pax}})(P_{\text{Pax}}) + (\text{Cargo}_{\text{Capacity}})(LF_{\text{Cargo}})(P_{\text{Cargo}}) \quad (12)$$

Where $\text{Seats}_{\text{Available}}$ is the total number of seats available on board the aircraft, LF the aircraft's load factor, P the price, $\text{Cargo}_{\text{Capacity}}$ the total cargo capacity of the aircraft and the

subscripts Pax and Cargo representing Passenger and Cargo respectively. The load factors in this instance is a measure of how much the aircrafts load carrying capacity is being utilised and ranges between zero and one, where a zero value implies an empty aircraft and one value implies a fully loaded aircraft.

Operating costs per flight (C_{Op})

This is the total operating costs incurred by the airline to operate the aircraft. [118] The costs are usually split into two main headings, direct (DOC) and indirect (IOC); and may be split down further into fixed or variable depending upon the preference of the airline operator. The direct costs refer to costs incurred during flight operations such as fuel costs, crew costs, aircraft insurance and depreciation. Indirect costs on the other hand refer to expenditures incurred by administration, customer service and advertising for example.

Delay and cancellation costs per flight ($C_{D\&C}$)

The delay and cancellation costs are the cost sustained by an airliner when a scheduled flight fails to depart on time. Ferguson et al. [119] provide one method of calculating these costs and is the method chosen within this research. Although this method may appear simplistic, the approach allows designers to calculate the anticipated additional expenditures suffered by the airline early within the design phase; specifically the additional crew costs, the additional fuel costs and passenger compensation during these delay and cancellation periods.

Externality costs per flight (C_E)

The externality costs are essentially taxes applied to a system due to its negative impact on society. Currently these mainly concentrate on the environmental damage caused by operating an aircraft such as aircraft noise and CO₂ emissions. The purpose of these taxes is

to give designers incentives to develop quieter, more fuel efficient and environmentally friendly aircraft which will benefit everyone not just aircraft passengers or airlines.

Manufacturing costs per aircraft (C_m)

These are costs incurred by the producer to build the aircraft. They include all of the costs sustained to fabricate and assemble the aircraft. It is possible to estimate these cost by employing the methods developed by Roskam [118] and Raymer [120] but more accurate costs estimates would be achieved by analysing similar projects previously performed by the producer.

Disposal cost per aircraft (D_{Disp})

The disposal costs are the cost incurred by an airliner to retire an aircraft from its fleet. The cost of this disposal is highly dependent upon how the aircraft was manufactured, operated and the location where the aircraft is retired. To estimate this cost, this research uses the approximation found in Roskam [118] and Ghorbany and Malaek [121] which shows the disposal costs of an aircraft to be 1% of the aircraft's total lifecycle costs. This approximation however is based upon traditional aircraft designs and as designs become more complex and incorporate ever higher percentages of composite material, this percentage may change. Given the current unknown of how to safely and environmentally dispose of composite components future predictions indicate that the disposal cost of tomorrow's aircrafts will unfortunately increase.

It should however not be forgotten that operators may sell their aircraft to another airline before their expected end of service life which would generate revenue rather than an expense.

Research and development costs (C_D)

The research and development costs are the costs associated with engineering and designing the new aircraft. Roskam [118] defines this cost as the summation of the costs incurred when engineering and designing both the airframe and engine, the development support and testing costs, the aircrafts test flight costs, the aircrafts test flight operation costs, the cost of the test facilities and financing costs.

3.3.5.2 A Review Of The Surplus Value Objective Function

The current surplus value objective function (stated as Equation 10) offers many advantages over the traditionally used measures. This section provides a summary of these benefits as well as its limitations.

Advantages

Surplus value is an all-encompassing objective function which is capable of considering the views of multiple stakeholders simultaneously when making a decision. This allows the designers to make the better trade-offs for all stakeholders rather than just focusing on one or two aspects as previous functions have done.

The surplus value objective function is an overarching function which evaluates the complete system rather than just one particular component or subsystem. This ensures that the best overall system is designed rather than combining many optimal subsystems together in the hope that it creates the optimal system.

The surplus value function allows the design team to easily evaluate different designs by producing one unique numerical score for each design based upon the economic value it provides to its stakeholders.

Due to the benefit of the unique value score designers can always select the best design option for the stakeholders from a range of available options i.e. the design option which has the highest surplus value score.

Surplus value considers the economic value of a system throughout its complete lifecycle rather than just one stage of systems lifespan. In doing so it ensures that the system provides long term value rather than simply minimising initial costs which could potentially be eroded or wiped out in later stages by high operational, maintenance or disposal costs, creating great dissatisfaction to the system's stakeholders.

The surplus value equation provides designers with a transparent, traceable and repeatable method of making decisions without designer preference interfering within the selection process. It achieves this by always selecting the design option which creates the highest surplus value score.

Limitations

Like the Value Driven Design process, the surplus value objective function is still within its infancy and to date it has been mainly be applied to individual subsystem designs. Cheung et al. [56] for instance developed their equation specifically for use in aircraft engine design which may neglect the effect these choices have on other subsystems. It is only when the objective function is applied at the system level will this limitation will be removed and the advantages it promises be delivered.

Surplus value is purely an economic function which at present only considers the monetary worth of a potential design to its stakeholders. While economic value should not be dismissed as it is a very important aspect of any design, it does not fully and therefore accurately represent the true value of a design. While the founders of the surplus value equation do not object but rather encourage the inclusion of non-monetary terms within

the surplus value equation; including these terms is difficult as they first must be monetised to ensure that a unique value score is retained. For this to be possible, the approach assumes that all non-economic metrics can be monetised but is this possible and/or appropriate? For instance, how would or even could safety aspects be monetised and justified? Simply omitting these terms does not create the desired value function as it ignores important needs to many stakeholders.

Despite this limitation value functions are seen as vital tool within the new design process and would be greatly be enhanced if this issue could be overcome. One of the aims of Chapter 4 is to resolve this concern by developing a method to easily incorporate both economic and non-economic values within the value function.

3.4 Models

Models are one of the most important tools used within design as they assist designers make choices. A models purpose is to bring forward knowledge about the design allowing better decisions to be made early within the systems development. A model is a simplified representation of reality used to predict possible outcomes. [122] Models used within design are mostly mathematical, based on a number of variables which the designer can alter to obtain information. There major uses are:

- 1) Determining the effect of changing a system attribute has on a systems response (sensitivity analysis)
- 2) Identifying potential showstoppers
- 3) Performing rapid trade studies
- 4) Provide designers with a better understanding of problem and its required solution

Models can be simple or complex depending upon the scenario and the level of accuracy required. System models are usually complex due to the number of interactions between different variables/components. While modelling all of these effects reduces the error in the results; it ultimately increases the computational effort and time required to run each scenario. Employing a metamodel however can overcome these issues with only a small decrease in accuracy.

3.4.1 Metamodel

A metamodel is a “model of model” and provides an approximation of a more complex model. [123] They are designed to capture most, if not all of the significant effects of the original model but at a reduced computational cost. This simplification however inevitably introduces additional error into the modelling environment. Nevertheless their ability to efficiently explore and rapidly analyse the solution space compensates for this increased inaccuracy.

There are many techniques used to build metamodels; each with the own advantages and limitations. The two most common methods in system design are response surface methodology and neural networks.

Neural networks establish relationships by mimicking the operations of the human brain. The process uses Bayesian logic (past results to predict future events) and artificial neurons which must be trained. Training is achieved by feeding the model a large data set along with any data rules. [124] How the model produces predictions however is not very transparent and for this reason is often seen as a black box technique. Neural networks are only as accurate as the quality and relevancy of the learning data and data rules entered into the model. Neural networks are incapable of accurately predicting outside the region

defined by the learning data but it is possible to add/update the learning data to represent new regions enabling the model to predict in these areas.

The response surface methodology is the more widely used technique in system design and the chosen technique for this study. The major benefit of the approach is that the equations are transparent; design variables are explicitly stated. In addition it being relatively quick and simple to create and use. After the equations have been determined the designer can start trade studies which are updated in real time without the need to rerun the simulation.

There are instances in design when the relationship between a system response and a set of design variables is either too complex to define or unknown. The response surface methodology however approximates this relationship through an empirical generated polynomial function. [125] The equations used in this research is assumed to be a second order, based on a Taylor series approximation, and follow the form

$$R = b_o + \sum_{i=1}^k b_i x_i + \sum_{i=1}^k b_{ii} x_i^2 + \sum_{i=1}^{k-1} \sum_{j=i+1}^k b_{ij} x_i x_j + \varepsilon \quad (13)$$

where, R is a given system response of interest, $x_{i,j}$ is the independent variables, k is the number of independent variables, b_o is the intercept of the model, b_i is the regression coefficients for the first order terms, b_{ii} is the regression coefficients for the pure quadratic terms, b_{ij} is the regression coefficients for the cross-product terms and ε is the error associated with neglecting higher order effects. It should be noted at this point that response surface equations are not limited to second-order approximations as higher order relationships and transformations may be used.

To determine the regression coefficients in each equation, multiple regression techniques are applied to a given data set. [125] If these regression techniques are unable to generate

an equation, it indicates that the relationship between the variables is highly complex and non-linear. In instances such as this another method e.g. Kriging [126] must be employed; as response surface equations are unsuitable for these problems.

To generate the data set required to create the second order response surface equations, multiple computer simulations of the original model need to run. To ensure that a sufficient data set is created a Design of Experiments will be employed within this research as this will ensure the metamodel would accurately represent the original model from the minimal number of runs.

3.4.2 Design Of Experiments

Design of Experiments (DoE) is a widely accepted tool used within industry to understand the effects which multiple inputs have on a response. The DoE is an efficiently planned and structured approach which alters various inputs to gain the maximum amount of knowledge from the least number of simulations. The advantage of manipulating multiple inputs at the same time is that the DoE can identify interactions which may have been neglected if only one factor was varied in each experiment. [125]

There are two types of DoE; full factorial and fractional factorial. The number of simulations required depends on which one of these is chosen, the number of variables, the number of levels and the number of interactions.

The full factorial is the most complete design, as all possible combinations are investigated, i.e. each factor at each level. Full factorials are balanced and orthogonal; both of which reduce error. Balanced designs are those where the inputs have been uniformly distributed across all levels. [125] An orthogonal design ensures that inputs may be assessed independently from each other. [125] A general DoE of a full factorial design with three factors, two levels and one response is shown in Table 4.

Table 4 – DoE Full Factorial Experiment (Three Factors, Two Levels And One Response)

Run Number	Factors			Response
	X ₁	X ₂	X ₃	
1	+1	+1	+1	R ₁
2	-1	+1	+1	R ₂
3	+1	-1	+1	R ₃
4	-1	-1	+1	R ₄
5	+1	+1	-1	R ₅
6	-1	+1	-1	R ₆
7	+1	-1	-1	R ₇
8	-1	-1	-1	R ₈

Note: As this is a representation of a fully factorial design, the factors in Table 4 are shown in their non-dimensional form. The +1 and -1 values however represent the chosen maximum and minimum values of each factor respectively.

The major disadvantage of applying a full factorial design however is the number of necessary simulations needed to fit the response surface. As the number of levels and factors increases the number of simulations grows exponentially according to Equation 14 [125]

$$\text{Number of Simulations} = (\text{Levels})^{\text{Number of Factors}} \quad (14)$$

rendering full factorial designs virtually impractical for scenarios which have many factors and levels. In situations where there are many factors and levels a fractional factorial design is a more appropriate.

The fractional factorial design is similar to the full factorial design but it requires fewer simulations to fit the surface models. The reduced number of simulations however ultimately causes a loss in information i.e. accuracy as not all effects are modelled. A key

property of a fractional design is its resolution i.e. the ability of a model to differentiate the main effects and the low order interactions from one another. [125] To ensure that this is the case and that no aliasing (undistinguishable effects) occur, a resolution of V was chosen for this study.

There are many types of fractional factorial designs available to create second order surface response models, all with their own advantages and limitations. Typical designs include Latin Hyper Cube and the Box-Behnken Design. The most commonly used design in industry however is the Central Composite Design (CCD) [127] which adds star points and at least one centre point to original factorial points. Star points are axial points which lie outside the original factor range used to estimate curvature.

Each of these three points plays a different role in surface response model creation. [125] The fractional points contribute in the estimation of the first order and interaction terms, while the star points contribute in the estimation of the quadratic terms. The centre points contribute in the estimation of the quadratic terms and provide an internal estimate of error.

Face Centred Central Composite Design's (FCCCD) are similar to CCD's but instead of having star points outside the original factor range they are contracted to sit in the centre of each design face. The contraction of the star points however creates some inaccuracy in the model as the desired rotatability property is lost i.e. the magnitude of prediction error is not constant. [128] Nevertheless the simplification of only requiring three level settings for each variable i.e. +1, 0, -1 reduces the computational cost and effort of creating the model for only a minor decrease in precision. [128] Additionally it removes the necessity to model beyond the variable bounds which may not be possible for all variables i.e. it may be an infeasible point. Further benefits of using a FCCCD is that they test the extremes of design space; minimising the extrapolation error and provide high quality predictions throughout

the complete design space. [129] For these reasons FCCCD's were chosen in this study. An illustration of a three factor face centred central composite design can be seen in Figure 16.

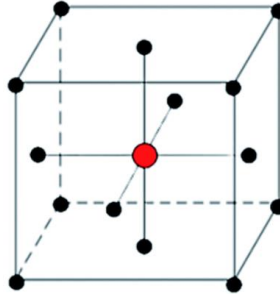


Figure 16 – Face Centred Central Composite Design (3 Factors) [127]

Typically it is recommended that three to five centre points are required to obtain a good estimation of random error. [128] However since this research uses a computer model to develop the desired aircraft only one centre point is required as random errors in computer simulations are assumed to be negligible since they are repeatable.

In this research the Response Surface Equations will be generated using a statistical analysis package known as JMP (version 9), the steps of which are outlined in the next section.

3.4.3 Creation Of Response Surface Model

Step 1 – Establish the Design Space

The first step in creating a response surface model is to identify all of the design responses that are of interest to the system stakeholders. Once this is known expert knowledge, brainstorming and QFD techniques can help the designer establish the input variables of these responses. The variable range i.e. the maximum and minimum value of each variable is also determined at this stage to define the limits of the design space within the metamodel.

The number of input variables identified for each response can be relatively high; with most only having a minor effect on the response. As the number of simulations runs increases

considerably with each additional variable; it is important that only the most significant contributors are modelled to maintain the accuracy of the model but to reduce the computational effort required to create it. To identify these variables screening tests will be performed. A screening test indicates the relative influence each variable has on the variability of a particular response. The larger the influence the more significant the variable is deemed to be to that response. The results of a screening test are usually presented in a Pareto plot as illustrated in Figure 17, where the bars indicate the influence of each variable while the cumulative curve tracks the overall response. Variables which exceed a certain influence value (predetermined by the designer) are then retained to be incorporated within the response surface model while all other variables are set to an optimal baseline value, determined by the experts.

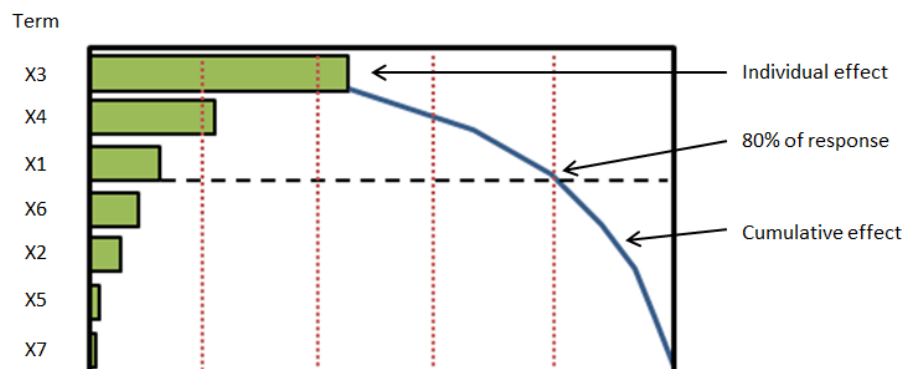


Figure 17 – Variable Screening Test

Step 2 – Generate and Complete DoE Table

The next step is to generate and complete the DoE table. In this research a Face Centred Central Composite Design will be used due to the reasons already mentioned. The JMP software will be used to generate this design. After entering all of the responses, design variables and their ranges into the software a DoE table will be created. This is the complete list of original model simulations which will be required to be ran to build the

metamodel. After each simulation is finished, the response values need to be collected and entered into the JMP software to complete the DoE table.

Step 3 – Build the Response Surface Model

Once the DoE table is fully populated multiple linear regressions analysis can be performed to determine the unknown coefficients (b_o, b_i, b_{ii}, b_{ij}) in Equation 13. The error term (ϵ) however is assumed to be a random; normally distributed with a mean of zero. This is verified in the next step. The linear regressions analysis in this research will be performed by the JMP software which uses a least square approach to minimise fitting error.

Step 4 – Model Validation

The final step is to validate the predictive ability of the response surface model and its completeness. This will be done by performing a statistical check, an error check and a validation check.

1) The statistical check

The coefficient of determination (also known as R-Square or R^2) is a mathematical measure of how well the assumed function can explain the variability in the response data. The value of R^2 ranges between zero and one; with one being a perfect fit. An actual verse predicted plot as shown in Figure 18 illustrates the actual values plotted against the predicted equation.

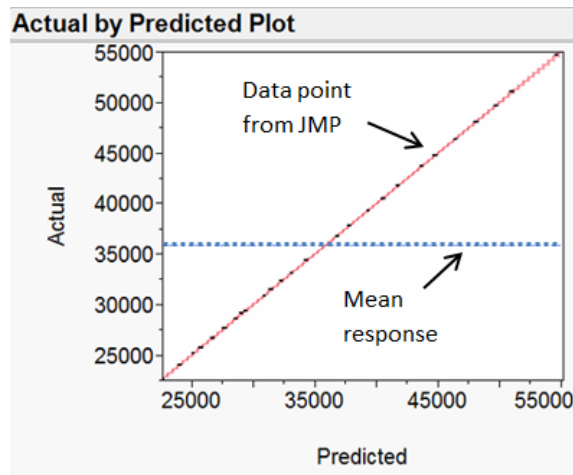


Figure 18 – Actual Vs Predicted Plot

An even distribution along the fit line indicates a good fit. If clumping occurs along the line it indicates that one or more independent variable is driving the response. All points which lie far from the regression line (outliers) need to be investigated to determine why the model is not predicting them very well. The R^2 value is calculated using Equation 15. [130]

$$R^2 = \frac{\sum_{i=1}^n (\hat{y}_i - \bar{y})^2}{\sum_{i=1}^n (y_i - \bar{y})^2} \quad (15)$$

Where y is the actual data point, \hat{y} is the model prediction and \bar{y} is the sample mean

In the field of engineering R^2 values above 0.90 are considered strong relationships and therefore adequate for this research. In other fields such as social science where human behaviour is poorly understood, never mind predict, the R^2 value could be significantly less (e.g. 0.3) but still considered strong. [130]

2) The Error Check

The difference between the actual response value and the predicted value is called the residual error. The smaller the residual error the better the model predicts a particular point. Residual plots are used to verify the assumption that the error value in the model is

normally distributed about zero. A good residual plot is shown in Figure 19 which displays the error in a random “gunshot” appearance about zero.

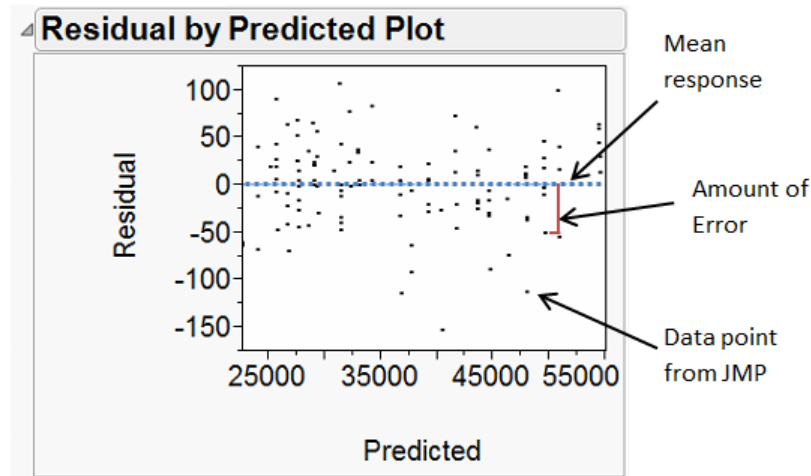


Figure 19 – Example Of A Good Residual Plot

If the residual plot shows a sign of clumping it indicates that one or more independent variable is driving the response or the response is discrete. A clear pattern on the plot however indicates that a 2nd order model is not sufficient as higher order effects are present in the data. The residual value of each point is calculated using Equation 16. [130]

$$\varepsilon = y - \hat{y} \quad (16)$$

Where y is the actual data point and \hat{y} is the model prediction

3) The Validation Check

If the model has passed both the statistical and error checks the final test is to perform a validation check. The validation check is used to confirm the predictive ability of the model. To determine this, an independent data set (i.e. data not used to create the model) is randomly selected from within the variable ranges. The data is then used to run a set of simulations using the original model while it is also predicted using the metamodel. If the residual value between the simulation and prediction results is small then predictive ability of the model has been confirmed. Although performing this check increases the

computational effort of building these metamodels it is the only method available to ensure the response surface equation accurately predict the behaviour of the response.

3.4.4 Techniques To Improve Goodness Of Fit

If the model fails to pass all of the above checks there are four techniques which can be considered to improve the goodness of fit. The first technique is the exclusion of high residual points used to create the model. The second approach is to identify and include higher order effects which may be influencing the model. For example a combination of variables which was initially assumed to be negligible should also be included in the model. Checking the screening tests can identify these combinations. The third technique is to transform the responses with logarithmic or exponential functions based on expert or scientific knowledge. The final and least desired of all the techniques however is to redefine the input ranges but this fails to model the area of interest and means the process need to start again.

3.5 Summary

The aim of this chapter was to identify key elements within the current state of art methods which should be retained or altered within the new design technique. The chapter began by briefly reviewing the limitations within the current state of the art methods, highlighting the aspects which the new design methodology aims to address. Following this review, requirements and their role within the design process was examined before introducing the theory of fuzzy logic as alternative method of capturing stakeholder needs.

The role objective function(s) have within the design process was then analysed. As a system level value function is seen as a vital tool within the new design process, it was important to get an understanding of how these functions are developed. To achieve this, a review of existing design optimisation methods and objective functions currently employed

within the design community was performed. As the new technique would be using a single overarching function, the review emphasised the need to formulate this function correctly to ensure the designers make the best choices for the stakeholders. The review also highlighted the need to move towards a value function rather than using a traditional requirement based evaluation which focuses typically on one aspect such as weight or cost. Value functions are seen as superior functions as they are able to combine the needs and views of multiple stakeholders within one function, providing a more balanced evaluation criterion for the design trade-offs which must be made.

To date, value functions have predominantly been used within the Value Driven Design technique with surplus value being the metric of choice for many studies. While this metric has demonstrated that it can consider the views of multiple stakeholders (passengers, manufactures, operators and society) during the decision process, it does have one major limitation; the metric is purely economic. While the inclusion of non-monetary terms is encouraged by the founders of the equation; including these terms is difficult as they first must be monetised to ensure a singular value score is retained. Simply omitting these terms however does not create the desired value function as it ignores important needs to many stakeholders.

The focus of the next chapter is therefore to develop a method of easily incorporating both economic and non-economic values within the value function. Chapter 4 also aims to answer two fundamental questions about value; how it is defined and who ultimately decides what value is?

The final section in the chapter provided a brief overview of models and their use within the design process. It explicitly addresses response surface models which will be used to create the modelling environment within this research. How they are created, validated and techniques that can be employed to improve goodness of fit are all discussed.

Chapter 4: Value

Ever since business adopted the phrase “you cannot improve what you do not measure”, metrics have been an important part of the management process. Timely, detailed and accurate metrics have the ability to assist management and designers in many areas, including making better choices. This however is only guaranteed if the correct metric is chosen; as a poorly selected metric can unfortunately and unintentionally lead designers to make the wrong choices. [131]

Take for example a call centre manager who wishes to improve customer service. One of the major issues with the call centre is that it is taking too long for customers to talk to an advisor. The manager analysis the situation and discovers that the efficiency of the call centre is below average and needs improved. The efficiency of call centre is linked to the time it takes for each employee to resolve a customer issue. If this time is reduced, the efficiency of the call centre will increase as more calls can be handled per day. To increase the number of calls handled each day, the manager begins to measure the time each employee spends on the telephone and introduces incentives for employees who deal with the most calls per hours. While this seems logical and the reasoning behind the metric makes sense, is it correct? Remember the goal was to improve customer service. Incentivising the most calls per day however is actually encouraging employees to close calls as quickly as possible and move on; even if the customer is not satisfied with the solution. Therefore although management believe their customer service is becoming better as it is more efficient i.e. the calls handled per day is increasing, a discrepancy appears between what management perceive and what their customers experience i.e. poor customer service.

Humans are exceptional at finding loopholes and can quickly find ways to exploit them for their own benefit. In the above example the only metric recorded was calls per hour. Employees would quickly realise that simply ending a call without finding a solution would still lead to reward as quality was not recorded. This is known as “gaming the system” and while unethical, it undoubtedly occurs. To prevent this from happening, a metric which provides a balanced view of reality must be found which rewards both calls per hour and quality if the business is to improve its customer service. [132]

To date most of the value functions being applied during the Value Driven Design technique has been a modified form of the surplus value equation. Surplus value however is purely an economic function which considers only financial matters. If the value function is to design towards value, is surplus value the correct metric or has the use of the surplus value metric created a similar situation to the above call centre example.

The focus of this chapter is therefore to understand the term value and to seek an answer to a question currently unanswered within VDD technique; how value is defined in the context of system design? Additionally is the value of a system purely economic or is this only one of many elements within value? If other elements are important, what are they, are they always the same and how do you incorporate them within the value model? By answering all these questions it is hoped that a better value function will be created allowing designers to make better decisions.

4.1 Defining Value

Successful products provide value to their stakeholder’s and is therefore an important aspect of any design. [40] While designers understand how to design towards minimising cost, designing towards value is different story. This is because value is an extrinsic property (a property that depends on a thing's relationship with other things) whereas cost is an

intrinsic property (a property that a thing has itself, independent of other things, including its context). [45] Therefore while the concept is simple, improve the system's value and a better more desirable solution will have been created; implementing such an approach is not as easy or initiative as it first might appear.

Value is a term which everyone knows. Defining it however is complicated as there is no universally agreed standard for what it is [5]; making the task of designing towards "value" very difficult. This section discusses the concept of value and seeks to provide answers to the following two fundamental questions;

- 1) How is value defined?
- 2) Who ultimately decides what value is?

By answering these two questions it is envisaged that designers will better understand the term value while also providing guidance on how to construct the correct value function for their system.

The online Oxford English dictionary defines value as

"the equivalent monetary worth, with good value being offered when the worth of something is less than the price paid for it." [133]

By this definition, the value of an item is purely financial and explains why the value of an item increases when it goes on sale. For an item to be valuable though it must satisfy a need. Low cost items therefore have the potential to provide better value than more expensive alternatives if it can still satisfy the needs of the customer. Cheap products however do not always offer better value; especially when the operational costs outweigh the initial saving of purchasing the item, the item does not last as long or it causes the user to not enjoy the use of the product. Furthermore if value was simply financial and function

based the lowest cost item which accomplishes the desired need of the customer would always be chosen but this is not the case; as multiple products exist and compete within the same market place. A toaster for instance has one basic function, transform bread into toast; yet there are literally thousands of toasters which consumers can choose from. The Apple iPad is another example, compared to other tablets with similar technological specifications it is seen as expensive, yet it dominates the global tablet market [134]. Defining value as purely economic then is too limiting and misleading as it overlooks the other valuable aspects of the design which are also important to consumers. To establish the complete value picture, it is perhaps important to review how a customer chooses between different designs.

When people are presented with a choice (in this case a range of products) they rely upon past experience and all of the available information to make the decision. The product which they perceive to offer them the best value will be the chosen design. Value then is put into context by comparing different designs and drives selection. People however perceive value differently and explains why no universally agreed standard has yet been established. For example one person may value a work of art at one million dollars while another person may only perceive the same work of art to be worth ten dollars. This discrepancy nevertheless does allow one of the questions to be answered, who defines what is valuable about a design; the perceiver or in the context of system design its stakeholders. If designers understand what is valuable to its stakeholders the decisions they make will be much easier and smarter as they will be aligning with what the stakeholders want. Value statements are an excellent method of determining the valuable aspects of the design from each of its stakeholders and will be discussed in more detail in a later section.

Values should not be assumed to remain constant as they do change over time and although they change more slowly than needs it does not mean future trends should be

neglected. For instance stakeholders across all sectors are requesting that new products be more environmentally friendly than their predecessors because society has become more environmentally conscious than past generations. Additionally timing onto the market is another important aspect of value. Arrive too late and the value opportunity may be lost because the need has changed or a competitor has saturated the market. Arrive ahead of the market and the public may not perceive its value causing the product to flop. In either case only when society decides a product is needed will it be considered valuable.

As the system stakeholders define what is valuable, the system's value model becomes unique to each system and cannot be created without the inputs of stakeholders. This research however purposes that there are three fundamental aspects which determine a system's value; all of which must be considered and included within the value model. These aspects are a designs performance, economic and social characteristics and although they are discussed in a linear fashion, the evaluation can begin with any aspect.

The first aspect a design is usually evaluated on is its performance value. In other words does the system do what the stakeholders need it to do? If a system fails to meet a functional need it can significantly reduce the value of a product and in extreme cases render the design worthless altogether. A recent example of this was Apple's new navigation app, Apple Map, released in late 2012 to compete with Google's Google Maps. [135] The Apple Map app failed because it did not provide it users with a reliable navigation system as it often selected "dumb" routes (least efficient or an infeasible option of travelling between to places e.g. crossing a lake in a car where there was no bridge existed) which ultimately provided little or no value to its users. Being able to perform the functional needs of stakeholders is therefore an important aspect of value and one not to be overlooked.

The second aspect is usually the economic value of the product. The economic value of a product considers the financial aspect of the system from cradle to grave. Lowering costs and/or increasing the revenue potential of a design can provide better value to the systems stakeholders. An important economic aspect is its affordability. If the design is not affordable then customers must seek elsewhere for a different solution. Affordable however should not be limited to the purchase or rental price of the system but also include other costs such as operational costs as well as additional add-ons which may be important to various stakeholders. The cost of after sales care i.e. warranty, support to resolve unforeseen issues for example should also be considered in this section as it can persuade customers to purchase the product, even though they may never need it. Car manufacturers which offer long warranties for example may be able to persuade customers to choose their design over others due to this aspect even if the likelihood of the customer ever needing it is minimal. Both direct and indirect costs of a design are important and should be evaluated. Economics is therefore another important aspect of value.

The final aspect of a design is its social value. Social values are defined in this research as the values held by the stakeholders but not captured within the performance or economic value of the system. While performance values focus on the system's ability to accomplish certain functional needs, social values consider how this operation affects, interacts and/or is perceived by society. Understanding the culture of both the stakeholders and the market which the design will be operating within is a good place to start in identifying these values, as these values will be the expected norms of any new design. Many good designs have failed, such as the Whirlpool's world washer, because social values were not considered, even though the functional need (in this example to wash clothes) was the same. [136]

It is clear from the above discussion that a system's value is determined by the performance, economic and social aspects it offers its stakeholders. If designers are to

design towards value, the constructed value model must consist of these three aspects to allow a balanced evaluation to occur. Furthermore by considering these three aspects at the start of the process it will create a fuller picture of the system desired by its stakeholders and may identify needs unidentified through traditional requirement elicitation based methods.

The next section proposes one method of how stakeholder values can be identified, captured and combined within a value model; allowing the different design options to be evaluated and enabling the designer to quickly and easily determine the best, “highest value design” for the stakeholders. A simplified example is also provided to demonstrate the value function creation.

4.2 Creating The Correct Value Function

Creating the correct value function can be a difficult task even for the most experienced designer. To assist designers in this process Figure 20 proposes a systematic approach to capture and formulate the desired value function for any complex system.

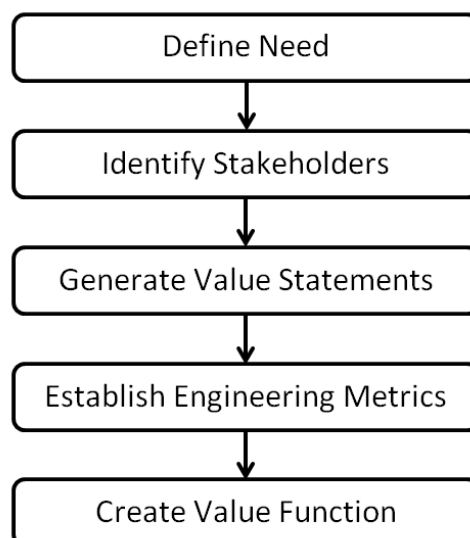


Figure 20 – A Systematic Approach For Creating A Value Function

Define Need

The first step in this process is to identify the need which has to be satisfied; without knowing this it is virtually impossible to create the correct value model. Time and care should therefore be spent to clearly articulate the need, to avoid models being formulated on vague descriptions which may unintentionally mislead the design team. Articulating the need however, is not the same as listing requirements, as requirements only define what the system must do to be acceptable and not the need itself. To avoid listing requirements the need should be expressed as a guiding statement of product intent, as the goal of this step is provide designers with a better understanding of the stakeholder need, not generate solutions. A justification statement should also accompany the need to communicate to the design team why the new system is required or why the current system is no longer acceptable, as this will enable the design team to focus on improving the aspects which have caused this new need to appear.

Identifying Stakeholders

Once the need has been established the next step is to identify all of the system stakeholders. To clarify stakeholders are people who have influence on the system design, either directly or indirectly and can come in a variety of sizes, forms and capacities. [5] Typical stakeholders include the end user, the financial backers, regulatory authorities and the public. It is important that all key stakeholders are identified at the beginning of the design process to ensure their needs and values are incorporated within the value model. Reviewing the stakeholder's involved in a previous design or one of a competitor is a good starting position for identifying potential stakeholders of the new system. The design team however should not restrict themselves to just these stakeholders but be encouraged to involve non-traditional stakeholders as well, to create an improved design. For example the drive for more environmentally friendly products has meant disposal personal are now

considered important system stakeholders in a new design; which may not have been the case five or even ten years ago. Remember a business cannot maximise value, if it ignores system stakeholders. [112] Additionally people naturally assume others see the problem the same way they do but different stakeholders offer different angles on the same problem. By including multiple stakeholders' especially non-traditional stakeholders, allows the need to be analysed from many different viewpoints; allowing everyone involved to better understand the problem before the work commences.

Not all stakeholders are created equally, as some will have greater influence on the design than others. For example it is common for a financial backer of a system to have more influence on the design than the maintenance team or the end user as it's their money being invested. Designers, however, need to look past the messenger and focus on the message they are presenting. If the message assists in improving the design, why does it matter who said it or how could other stakeholders argue against it if it is beneficial. It is often mistakenly assumed the customer needs and values are the only preferences that matter as they hold purchasing power. Systems though affect more than just customers and it is important that other people's values are considered, if the design is to be accepted by society or built by the manufacture. Solely focusing or listening to the needs and values of one stakeholder can therefore be disastrous.

Generate Value Statements

After all stakeholders have been identified the next step is to capture their value preferences; as this will determine the aspects of the design which make the system valuable. To capture these aspects of the design value statements need to be created by every stakeholder. A value statement is a written expression of what each stakeholder believes will add value to the new system. The statements can be written in natural language and do not need to be technical as their purpose is to provide a starting point for the

discussion on what aspects of the proposed system creates value with other stakeholders. Stakeholders should endeavour to keep these statements as concise and as relevant as possible without losing the meaning they are trying to convey. No word limit should be enforced on these statements but a guidance of no more than 35 words should be recommended to limit the amount of irrelevant information gathered. Not all stakeholders will understand why one stakeholder believes a particular aspect adds value, value statements can assist in this process. If the value adding aspect is obscure a justification statement should accompany the value statement to record and convey this information. If the reasoning is not shared it may be seen as unnecessary, needlessly increasing costs and reducing value.

To create these statements stakeholders should endeavour to answer the following four questions.

1) What aspects do you believe add value to this design?

This question forces the stakeholders to think of aspects which they believe add value to the design.

2) Why do you think that?

This question forces the stakeholder to provide reasoning for their suggestion. Simply asking which aspects add value will generate a list, answering this question will help the stakeholders and the design team understand why it does.

3) How do you know this?

This question aims to justify the suggestion. It asks the stakeholders to provide evidence which could be through what they have experienced or read.

If at this stage the understanding is clear there is no need to ask the final question. However if further clarification is required the fourth question may be able to help.

4) Can you tell me more?

While this question is open ended, it will ask the stakeholder to extend their reasoning with the aim of sharing further reasoning to their suggestion.

The benefit of following these simple questions is that it will force stakeholders to truly consider what makes the design valuable instead of just generating a list with little thought or effort.

Some may believe that this information could be captured using a simpler rating based system such as that used in the hospitality sector. This method however does not capture all of the information required to understand the individual needs of each stakeholder as the above questions would. For instance hotels are always seeking to improve the satisfaction of their customers. To determine which aspects their guests enjoyed they usually ask them to complete a quick survey at check out; which is generally based on a 5 star rating. Common metrics include "Cleanness of rooms", "Friendliness of Staff", etc. The issue with this method however is the information collected is generally not helpful. For example receiving a high star rating, does not guarantee future high scores as the metrics the guest used to determine this score was not recorded. Similarly if a low score is recorded, management do not know what aspect to improve as the metrics the guest used to determine this score was not recorded.

Another important method of identifying valuable aspects of the new system is through the study of how the current need is satisfied. The most basic of these techniques is observation where someone (usually a person part of the design team) watches another person fulfil the need. The major advantage of observation is that it can discover important

value aspects often omitted by stakeholders because they feel them to be so basic and/or obvious that they go without saying. Interviews, focus groups and questionnaires are additional techniques which can also produce similar results and highlight any missed stakeholder needs or values.

While it is important to understand the aspects which the system stakeholders believe add value to the design, it is equally important to understand the value which competitor products offer. To discover this information a market analysis should be performed as it can identify needs and values important to the success of the new system which were unknown or uncommunicated by the system stakeholders. A further benefit of a market analysis at this stage is that it can ensure the desired system does not already exist. If this is true this information will assist the marketing team identify the systems unique selling point, allowing the new system to be easily differentiated from competitors while informing the design team the design aspects they should seek to focus on.

It is not uncommon to discover that different stakeholders have different value preferences which may conflict with their own values or the values of others. To give an example, stakeholders who do not plan to use the system might push for the cheapest option which fulfils the need but this means it will not be the most user friendly design. In contrast the end user might push for the most user friendly option which is not the cheapest option. In these situations the design team must ensure the correct balance is struck as if it's too expensive the design will not be chosen but if it's too difficult to operate the design will also be rejected by the end user.

Once all the information has been gathered, the design team should publish the findings in a value document to assist in the next part of the process. The value document will also help stakeholders understand the needs of other stakeholders and the aspect they believe add value and why.

Establish Engineering Metrics

The next step is to transform these value statements into engineering metrics to enable the design team to optimise the design. To achieve this transformation, this research employed the House of Quality (HoQ) tool developed within the Quality Function Deployment (QFD) technique. QFD was developed in Japan in the late 1960's [137] [138] but has become widely accepted in many industries across the world as a method of improving product quality. One of the most recognisable tools of QFD is the House of Quality which captures and documents the relationships between the customer need and the corresponding technical measure chosen by the design team. Therefore while past HoQ tools have focused on improving product quality, the process is seen as an excellent method of transforming value statements into engineering metrics. A major advantage of using the HoQ tool to accomplish this task is that it also weights the metrics within the objective function and the process can be reviewed in a clear and traceable manner. A blank schematic of the House of Quality tool can be seen in Figure 21.

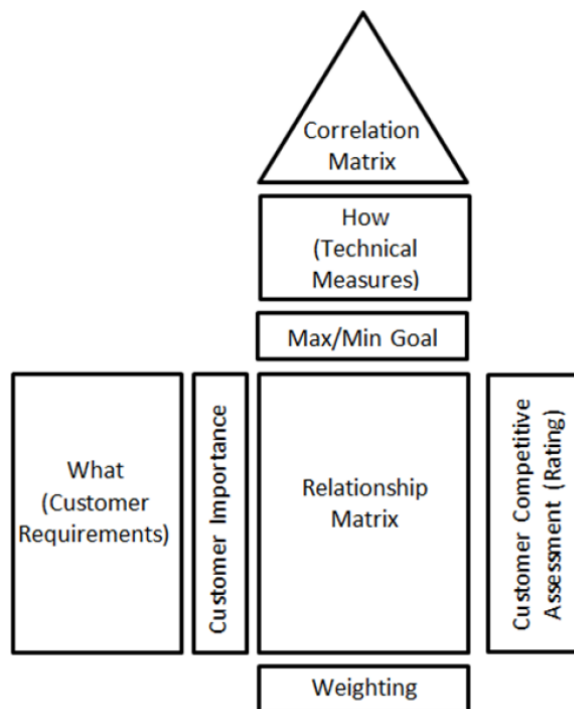


Figure 21 – House Of Quality [137]

In the traditional HoQ approach, the process begins by listing the customer needs into the left hand side of the house; described as the “What” room in Figure 21. The needs are often expressed in the customers own words and are qualitative in nature rather than technical. Common examples include product “Must be Safe” or have “High Build Quality”. Instead of using needs though, it is proposed that the technique is adopted to map the relationship between stakeholder values and the technical measures. Once all values have been entered the process would continue as a traditional HoQ.

The next step is to attach a weighting to each value, based on the preference of the stakeholders. This can be a difficult process to complete, especially when many stakeholders feel every value is important. In reality though there are values more important than others. For instance is the system being safe as equal/more/less as important as the system being stylish? Only the system stakeholders can answer this question. If stakeholders feel, every metric is equality important, designers should inform the stakeholders of the likely effects this choice will have on the final design using their past experience. Take for instance a car which can be designed to include additional extras such as air conditioning, built in satnav or cruise control. While the customer may believe everything on this list is important, when these extras are weighed against the financial cost of obtaining it, things which aren’t so necessary and are swiftly removed. Although cost is used in this example it should not be the only aspect considered, as social or performance aspects are important part of value and are also very persuasive to stakeholders. It should also be stressed that there are no governing rules which states that one particular value is always more important than another as it is purely based on the preference of the stakeholders at that time. Once a weight has been decided they are entered in the customer preference section in Figure 21. While other scales may be used, this research will employ the commonly used 1 to 10 scale.

After all the values and their weightings have been agreed and entered into the HoQ tool, the next step is to identify the engineering characteristics to measure each value. These are known as the quantifiable “Hows” and are entered into the “How” section of Figure 21. Selecting the correct metric however can be difficult even for the most experienced design team. It is therefore of the most important that the stakeholders are involved in this process to answer any queries the design team or any other stakeholders may have. Understanding the need and the values which the stakeholders are looking to promote can make this task a little easier but the metric chosen must reflect the stakeholder’s value.

All good metrics possess the following five qualities of being unambiguous, comprehensive, direct, operational and understandable. [139] Metrics with natural scales are therefore the best type of metrics to choose since they meet all of these characteristics. [139] For example if the mass of a system has to be measured, kilograms (kg) or pounds (lb) are equally good measures for this characteristic. Not all characteristics though have natural scales. System safety and quality for example are two important aspects of any design without natural scales. In circumstances such as these the designer is left with two options; construct a scale to measure the aspect or use a proxy measure instead [139]. A constructed scale typically has between two and ten distinct points defined by the designer to measure the characteristic. Constructed scales can be either qualitative or quantitative depending on the preference of the designer. Every constructed scale though requires documentation describing each point as without this information the process is purely subjective making it unreliable to compare different designs. [139] A common method of measuring system quality for example is represented graphically in Figure 22 which consists of five points labelled; poor, below average, average, above average and excellent.

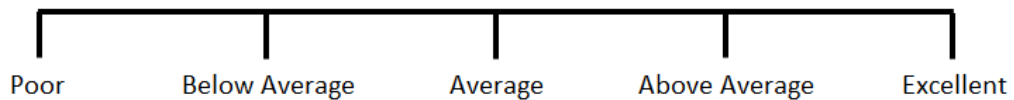


Figure 22 – Typical System Quality Scale

In contrast a proxy metric does not measure the characteristic directly but instead uses another metric associated with that characteristic. [139] Environmental damage for example has no natural scale but the number of toxins released in parts per million could be measured as a substitute, since toxins released are associated with environmental damage. Caution though should always be employed when using proxy metrics to ensure that they are measuring the correct aspect, as toxins released may not fully or accurately represent the meaning of environmental damage and may require additional metrics such as hazardous waste produced and/or the volume of water contaminated, to capture its meaning completely. Due to the qualities listed above it is always preferable to use natural scaled metrics over proxy metrics and proxy metrics over constructed metrics. Once a metric has been identified and agreed, its objective should also be established. If the metric is to be maximised i.e. more is better, an upward pointing triangle (▲) or arrow (↑) should be placed above the metric in the objective section of the Figure 21. On the other hand if the metric is to be minimised i.e. less is better, a downward pointing triangle (▼) or arrow (↓) should be placed above the metric in the objective section of the Figure 21. After all “Hows” have been identified and their objectives established, the relationship matrix is the next room to be completed.

The relationship matrix forms the centre of the house and records the correlation between the value statement and the engineering metric. There are four relationships which can be chosen including strong, medium, weak or none. [137] It is critical that all stakeholders are involved in this procedure to ensure that all expert knowledge and experience is captured

and the chosen correlation is correct. Many correlations may be obvious while others may not. In circumstances where a correlation is not clear a justification comment should accompany this correlation for traceability purposes. Admittedly this process is very stakeholder intense and it can be difficult to get all stakeholders together at the same time; not to mention come to a unified agreement but it is important that this is achieved to ensure that a comprehensive, verifiable and traceable objective function is created which truly captures and represents all stakeholder value. Once the relationship matrix is complete and agreed, the next step is to transform the qualitative relationship into a quantitative relationship by substituting a numerical score for every qualitative statement. A non-linear scale of 0, 1, 3 and 9 is typically used to represent the values of none, weak, medium and strong respectively; as this will help distinguish between the primary and less influential metrics. [137] The final step of the HoQ involves calculating the weighting section. To calculate the weight of each metric, the numerical value of each correlation is multiplied by the value weighting and then summed to determine the total value for that metric. The process is then repeated for all metrics. Once this is done the total value of each metric is summed together to calculate the total system value score. The total of each metric is then divided by the total system value score to give the weighting of each metric. The weighting calculated for each metric is then used as weighting factor for the metric within the value function.

Create value function

The final step is to create the value function using the information generated from the previous steps. A value function is an objective function which will be used to determine the value of each design option. This will allow designers to always make the best possible value trade-offs and select the highest value system on behalf of the stakeholders. There are two types of value functions which exist; the first is the measurable value function and

the other is the utility function. The major advantage of using a measurable value function is that the difference between scores is meaningful. [140] For example if Design A scores twice as many points as Design B, Design A provides double the value provided by Design B. With a utility function however the only conclusion which can be made from this example is that Design A is better than Design B. [140] Measurable value functions can only be used when no uncertainty exists. [140] Since this is not the case when designing a complex system and a utility function will be generated.

To date the means of developing a value function has not been well documented or agreed upon, especially within industry; yet it is a vital to the success of system. Nevertheless a good objective function, regardless of objective, guides the decision maker to make the best possible trade-offs. [141] A generic additive objective function is shown in Equation 17.

$$f(x) = \alpha x_1 + \beta x_2 + \dots \quad (17)$$

where α and β represent the relative weights and x the different attributes of the objective function. A common mistake is to have many attributes included within the objective function. This however can complicate matters and leave the decision marker unable to understand the results. Instead the objective function should only be as complicated as required with minor attributes which have no significant effect on the final result removed (i.e. screened out).

It is also important that the objective function creates a single score to allow designs to be easily compared. If all of the metrics within the objective function use the same unit, then the unit also becomes the unit of the objective function. For example if the objective function completely consisted of metrics in kilograms then the objective functions units should also be stated in kilograms. Value, however, considers multiple aspects of a system and it is unlikely that all of these aspects will use the same units. This leaves the designer

with two choices; either convert the metrics into a single metric as the current Value Driven Design methodology does or non-dimensionalise the metrics. Converting metrics into a single unit can be difficult to achieve and justify. This is one of major issues with the Value Driven Design technique. This research therefore purposes to non-dimensionalise the metrics. To achieve this, a baseline value must be chosen usually by the designer. If a metric must be maximised the value of the current design is divided by the baseline value. If however the metric is to be minimised the process is inversed with the baseline value being divided by the current designs value. [142] Equation 18 is the equation used when a metric has to be maximised and non-dimensionalised while Equation 19 is the equation used when a metric has to be minimised and non-dimensionalised. Additional information on creating these types of objective functions is provided by Mavris and DeLaurentis [143].

$$\frac{x}{x_{BL}} \quad (18)$$

$$\frac{x_{BL}}{x} \quad (19)$$

where x is the attribute and x_{BL} the baseline value of the attribute

By combining all of the above concepts together the proposed form of the value function becomes

$$f(x) = \left[\sigma \frac{P_1}{P_{1BL}} + \tau \frac{P_2}{P_{2BL}} \dots \right] + \left[\omega \frac{E_1}{E_{1BL}} + \dots \right] + \left[\mu \frac{S_1}{S_{1BL}} + \dots \right] \quad (20)$$

where P , E , S represent performance, economic and social metrics from the HoQ and

σ , τ , ω , μ the weightings from the HoQ process

Equation 20 however is not the final form of the value function as it is currently missing the desirability factor of each desirement incorporated within the value function. Note the

desirability factor is the transcoded form of the desirability function associated with each desirability incorporated within the value function. Their presence ensures that the stakeholder preference is accounted for within the value trades as without them designers would simply focus on aspects that have high weightings. Additionally failing to include them would assume linear value changes between the baseline design and the design being evaluated, which may not always be the case.

To demonstrate the above process the following simplified example has been created. The focus of the example is to create a value function for a family car similar to that of a Ford Mondeo or Volkswagen Passat.

Family Car Example

The first step is to define the need of the new system. This is achieved through the creation of a need statement which will state the goals of the new system and why the current system is no longer acceptable.

Need Statement

“Despite having strong demand and sale figures for our newest model, the overwhelming trend from the latest market research studies is showing that people are becoming more environmentally conscience and as a result want systems which reflect this. To anticipate this shift in preference and to remain complete within the family car market, a new more environmentally friendly vehicle needs to be created which retains the core values important to our existing customers.”

Once the need has been established, the next step was to identify the system shareholders. As the new system was replacing an existing design, analysing the stakeholders involved within the previous design i.e. the current or even older family car models was an excellent place to begin this identification. From this review it highlighted that the manufactures,

public authorities, insurance groups, general public, financial backers and the customer were all key stakeholders for the new system. However since the goal was to create a more environmentally friendly vehicle; the environmental agency and the clean energy department (at a local university) were also identified as major stakeholders within the new system.

After the stakeholders had been identified, value statements were created and then collected from each stakeholder. The purpose of the value statements is to capture and inform the design team of the design aspects which each stakeholder believes will add value. One of the many value statements from the customer for instance is listed below.

"I value a car which allows me and my family to travel safely without compromising on space or style."

From this statement the design team now know that the customer values a safe, spacious and stylish car with other value statements indicating that it must be economical and better for the environment than their current model. Other stakeholders had different views with the general public looking a quieter and less polluting vehicle. Once all these values had been gathered, the design team then published a value document to summarise and record these values. This not only assists in the next step but also helps stakeholders understand each other's needs and why stakeholders believe certain aspects add value to the design.

The next step involved transforming these values into engineering metrics. To accomplish this task the House of Quality technique was used. Since this is a demonstration of how the process works only a small subset of these values was selected and carried through, to reduce the complexity of the example. The five values chosen are shown in Figure 23. After entering the stakeholder values into the HoQ, the next step was to determine the relative importance of each value through a discussion with the stakeholders.

Metric selection can be difficult task but it is important that the metrics chosen reflect the stakeholder values. Once a metric has been identified it was discussed and confirmed with the stakeholders to ensure it captured the value correctly. After a metric was confirmed, its goal was established with the stakeholders to determine the non-dimensionalising equation to use within the value function. If the goal was to maximise the metric then Equation 18 was employed but if the goal was to minimise the metric then Equation 19 was used.

The final step was to complete the relationship matrix to obtain the relative weighting of each metric. The completed HoQ is shown in Figure 23.

Key
 ⊙ Strong Relationship
 ○ Moderate Relationship
 △ Weak Relationship
 ↑ Objective Is To Maximise
 ↓ Objective Is To Minimise

System Characteristics		Relative Importance	Maximum Speed	0 – 100 km/hr time	List Price	Fuel Consumption	Driver Visibility	Boot Capacity	CO ₂ Emissions
			(km/hr)	(s)	(£)	(km/litre)	(%)	(litres)	(g/km)
Stakeholder Wants			↑	↑	↓	↑	↑		↓
Performance	Responsive	3	⊙	⊙		○			○
Economic	Affordable	4			⊙	⊙			○
Social	Safe	5					○		
	Spacious	2			△			○	
	Environmentally Friendly	4	○	○		○			⊙
Relative Weighting			12.7	12.7	12.5	26.6	14.8	2.0	18.7

Figure 23 – House Of Quality For Family Car Example

The completed HoQ was then used to build the value function. The system characteristics and their relative weighting became the design variables and their weighting factors within the value function. Each variable was then non-dimensionalised according to the design goal (represented by the arrow directly below the system characteristic unit within the HoQ and the baseline value) to enable the value function to create a single value score. In this example the values of the existing car i.e. the car which this new design would be replacing was used as the baseline values.

To complete the value function, the final step was to incorporate the desirability factor associated with each desirability function. The desirability factor is essentially a correction factor applied to the non-dimensionalised score, to include the desire of the stakeholder within the evaluation criteria. If no desirability function has been defined by the system stakeholders for a particular system characteristic, the desirability function is assumed to have a constant value of one.

Only one desirability function was defined by the system stakeholders in this example. It was for CO₂ emissions and is illustrated in Figure 24. The creation of these functions is demonstrated in Chapter 5 and not shown here. Referring to Figure 24, if the new car design has a CO₂ emission of 100 g/km or 115 g/km, the CO₂ desirability factor (DF_{CO₂}) within the value function would be 0.9 and 0.5 respectively at these occurrences.

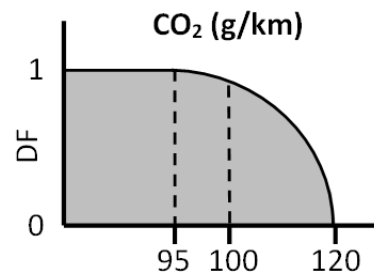


Figure 24 – Car CO₂ Desirability Factor

Adding the CO₂ desirability factor (DF_{CO₂}) to the results of the HoQ, the generated and final form of the value function for this car example is stated as Equation 21.

$$\begin{aligned}
 f(x) = & \left[12.7 \frac{x_{\text{Maximum Speed}}}{x_{\text{Maximum Speed BL}}} + 12.7 \frac{x_{0-100 \text{ km/hr time}}}{x_{0-100 \text{ km/hr time BL}}} \right] + \\
 & \left[12.5 \frac{x_{\text{List Price BL}}}{x_{\text{List Price}}} + 26.6 \frac{x_{\text{Fuel Consumption}}}{x_{\text{Fuel Consumption BL}}} \right] + \\
 & \left[14.8 \frac{x_{\text{Driver Visibility}}}{x_{\text{Driver Visibility BL}}} + 2.0 \frac{x_{\text{Boot Capacity}}}{x_{\text{Boot Capacity BL}}} + 18.7 (DF_{CO_2}) \frac{x_{CO_2 BL}}{x_{CO_2}} \right]
 \end{aligned} \tag{21}$$

4.3 Summary

The focus of this chapter was to understand the term value and to seek an answer to a question currently unanswered within VDD technique; how is value defined in the context of system design? The chapter revealed that value is extrinsic property of a system; which varies depending upon the relationship the system has with other things. Although this makes value difficult to describe it was discovered that system stakeholders define what is valuable about a system and therefore have an important role in the creation of the system's value function. While there is no universal value function which can be applied to every design problem, due to value being unique to each system and its stakeholders, the chapter highlighted that defining value as purely economic is too limiting and does not reflect a systems true value. It was proposed that the value of a system is a balance between the performance, economic and social aspects the design offers to the stakeholders when fulfilling a need (or needs). If an accurate value evaluation is to occur, these three aspects must be incorporated within the value function. Incorporating non-economic metrics within the surplus value equation however is difficult as they first must be monetised. This research however proposed that a non-dimensionalised value function be employed to avoid this difficulty. The chapter concluded by outlining a possible method of how to create this non-dimensionalised value function through a simplified example.

Using all of the information gathered so far the next chapter presents the novel design methodology known as Value Seeking System Design which aims to remove the concerns within the current state of the art techniques (SE and VDD) while retaining their advantages.

Chapter 5: A New Framework: Value Seeking System Design (VSSD)

In this section an innovative value seeking design methodology will be presented. Its aim is to remove the concerns associated with the current System Engineering and Value Driven Design techniques (highlighted at the beginning of this thesis) while retaining their advantages. A detailed description of the steps involved within this new methodology is provided and have been written in generic form to enable the technique to be applied for the development of any complex system. Like the current Value Driven Design technique an all-encompassing objective function will be utilised to assist designers in their decision making. The creation of this function was demonstrated in section 4.2 and will not be repeated here.

5.1 The Value Seeking System Design (VSSD) Methodology

Figure 25 provides an overview of the steps involved within the proposed design process known as Value Seeking System Design (VSSD). These steps will now be discussed.

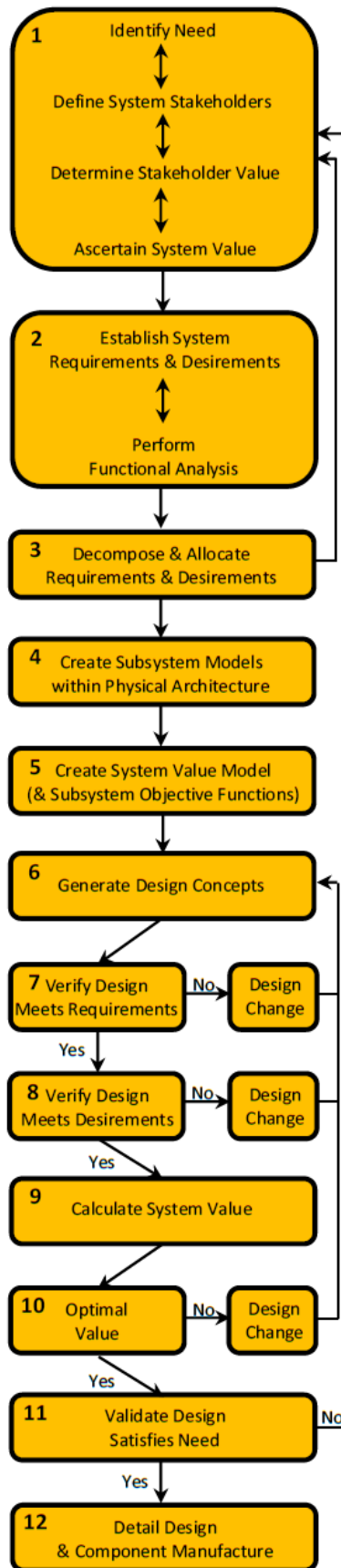


Figure 25 – Value Seeking System Design Methodology

Step 1 – Identify need, stakeholders and values

Like any design methodology the proposed technique begins by identifying the need which requires a solution. In most instances this is obtained through a conversation with the customer/marketing team or a request for proposal, depending upon the industry. At this stage the needs can be vague or subjective as its purpose is to give an initial understanding of the problem to the designer. Once the need has been determined a list of stakeholders can be identified. Stakeholders can come in many shapes, forms and sizes but are essentially any person or group of people affected by the system's creation, operation and/or disposal. It is important that all stakeholders regardless of their financial influence are identified early, as this avoids or at least reduces the likelihood of omitting needs which may be difficult to incorporate later within the design process. When determining the needs from each stakeholder it is also important to document the aspects of the design which each stakeholder believes alters the value of the design, as this will allow the designers to better understand the need they are trying to fulfil. While some of these aspects might appear obvious, depending on the system to be designed, the task may highlight any misperceived conceptions which the design team may have, as well as draw special attention to aspects currently unknown to them. Again simple statements written in non-technical language is ideal at this stage as the objective is to allow the designer to understand the wants and desires of the system from the stakeholder's perspective.

Once all stakeholder needs and values have been collected, the final part of step one is to create the system needs and values. The goal of step one is to document the system's purpose (i.e. the need(s) it will fulfil) along with its values. This is achieved by combining the individual needs and values of each stakeholder into one. While the needs of some stakeholders will overlap, different stakeholders will have different desires from the final system. This highlights the importance of including all stakeholders at the beginning as

these needs and values may be missed if only one or two stakeholders are considered. By summarising all of the information collected so far into a single document, a fuller picture of the system required is presented, allowing everyone to understand, discuss and agree the system to be built before design solutions are generated. The purpose of step one is to bring unity between all stakeholders on the required system not to generate or suggest solutions.

It is important to take time and effort throughout step one to ensure that all needs, stakeholders and values are identified correctly. While project pressures may try to rush this phase avoid taking short cuts as this will reduce the likelihood of redevelopment work later in the design stages which may be costly in terms of money and time to correct, if at all possible. Stakeholders are a vital part of any system and hold a wealth of knowledge. They are the key to understanding the need and the system's value. Let them know this and encourage open dialog, as it is the information they provide which will drive the rest of the design.

Although this step has been described as a linear method, the process is in fact cyclic and may require much iteration to perfect. This is because needs identify stakeholders, who define value, both of which are used to describe the system purpose and values which may lead to new needs or stakeholders etc. Only when the stakeholders are in unison and all the system needs have been identified should the process move to the next step.

Step 2 – Define system requirements and desirements

It is not uncommon to discover the information gathered from stakeholders so far is often vague and easy to misinterpret. The problem stems from the fact that human use norms throughout conversations to quickly communicate information. Upon hearing the word car for example, it is easy to visualise a vehicle, with four wheels, carries about five passengers

and a boot to store items. Additionally people know that a big mouse is smaller than a tiny elephant and a fast moving tortoise does not move as quickly as a fast car without being told the size of the animals or the speed of the tortoise or car. While this enables a conversation to flow, it is very difficult to design towards, as a misinterpretation here can make the design destined to fail from the beginning. Traditionally at this point, the System Engineering process would transform these needs into requirements using Boolean logic to remove any ambiguity. The VSSD process however recommends that these needs be transformed into both requirements and desirements, where requirements are needs defined by Boolean logic and desirements are needs defined by fuzzy logic. Both requirements and desirements will assist in the verification process.

Requirements are statements which the system must conform too, having a clear boundary between acceptable and nonacceptable. There are two basic types of requirements, functional and non-functional. A functional requirement defines what the system must do for its stakeholders whereas a non-functional requirement details how the system should behave. For example an aircraft must transport 150 passengers (functional requirement), the aircraft must conform to all FAA regulations (non-functional requirement). Desirements on the other hand have flexible boundaries with stakeholders willing to accept a point within a range if it improves the overall value of the design. To highlight the difference consider the following example.

During the development of a new system a stakeholder has stated that the system must be fast. Fast, however, is subjective and can be easily misinterpreted, even with context. A fast car for example could mean it has a high top speed but a high top speed can mean different things to different people depending upon their experiences. To overcome this problem the System Engineering process seeks to define this need as a requirement, to remove any misunderstanding between the design team and the stakeholder. Using the above example

of a fast car and having a further discussion with the stakeholder, the need was redefined as

“The system must be capable of at least travelling at 200 km/hr when operating under normal conditions and in a straight line”.

This statement removes any doubt in what the stakeholder is requesting allowing designers to make choices to achieve this target. Designs that are capable of travelling at or over 200 km/hr are therefore defined as acceptable while designs that do not are deemed unacceptable. This transformation however does create its own unique problem; it forces the stakeholder to agree a precise boundary between what is acceptable and what is not, which can often be difficult, especially if the decision has to be made by a group of stakeholders over a linguistic description.

In reality linguistic descriptions do not have a precise boundary between one state and another but instead gradually change, as the temperature example demonstrated within chapter 3. These needs should therefore be captured as desirements not requirements. Going back to the example with the fast car, the stakeholder is unlikely to argue that a car travelling at 198 km/hr is slow and only once it reaches 200 km/hr or above can it be considered fast as it's only a marginal change of 2 km/hr, a change anyone is unlikely to notice. Before the discussion it is likely that the stakeholder had a range which they believed constitutes “fast” rather than a definitive point. To this stakeholder fast may lie between the range of 180 km/hr and 220 km/hr or 200 km/hr and 250 km/hr. This information is lost when defining needs as requirements but could be retained through desirements. Merely creating a range however does not transfer all of the information over to the design team, as it does not indicate the preference of stakeholders within this range. While 180 km/hr may be acceptable to the stakeholder, they ideally want the top speed to

higher than this. To overcome this problem a simple preference statement should accompany every desirability. For example

“Increasing the systems top speed adds value to the system but only to the upper boundary as beyond this point, the design is going beyond the required need.”

To record and quickly transfer this information to the design team as well as other stakeholders Design Desirability Function (DDF) need to be created. They are based on the membership functions of fuzzy logic with a zero membership value indicating non acceptable whereas a membership value above zero indicating acceptable. A membership value of one is the preferred preference of the stakeholder with the membership values between zero and one indicating the stakeholder’s degree of acceptability at that point. Consider Figure 26 which represents the stakeholder’s belief of what constitutes fast in the previous example. Studying Figure 26, it becomes clear that the stakeholder’s definition of fast is between the range of 180 km/hr and 220 km/hr as speeds below 180 km/hr and above 220 km/hr have membership values of zero. Figure 26 also illustrates that 220 km/hr is the preferred preference as it has a membership function of one but going faster than this goes beyond the stakeholders need. Knowing this information the design team can focus their efforts on obtaining a design with a top speed of 220 km/hr as obtaining a design with a lower top speed is undesired.

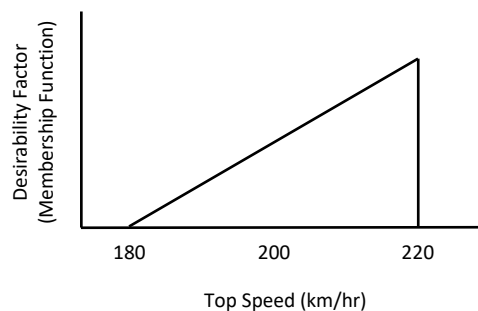


Figure 26 – Stakeholder Top Speed Design Desirability Function

One of the major advantages of using fuzzy logic to capture this information is that it allows the discussion to be more transparent, as every stakeholder can quickly see the similarity or difference between each other needs and values. During the discussion avoid letting stakeholders who own a position of authority from setting their preferences as the systems preferences as the system must satisfy many stakeholders not just a few. Instead encourage open dialog requiring justifications as this allows all stakeholders to engage in the discussion and assists in the traceability of every need.

To assist stakeholders create the required design desirability functions Figure 27 proposes a systematic approach to completing this task. The first step in the process involves establishing the range of values which the stakeholder would find acceptable for a particular aspect as well as the desired value. Once this has been determined, the remaining steps simply build the function within this range.

Figure 27a illustrates the completed first step with point D indicating the desired value and letters L and U indicating the lowest and highest acceptable values respectively. To build the remaining function, it is recommended that construction lines be drawn between these points as indicated by Figure 27b. The construction lines split the acceptable space into sections making it easier to build the function in steps rather than all at once. In Figure 27b, five equal vertical construction lines were added, this however is only a recommendation as the actual number of construction lines and their placement is at the discretion of the stakeholder. The construction lines will be used to create a guide line. The guide line is a visual representation of the stakeholder's initial attempt to define their desirability for this aspect. After creating the construction lines, the stakeholders then use these lines to define intermediate points within the desirability function. The middle construction line for instance is half way between the lower and upper values. At this value there is a desirability of 0.65; this is marked accordingly as Point C in Figure 27c. Points A, E and F on Figure 27c

are created in a similar manor. Since the desired point already resides on one of the construction lines (the outer most left line), this construction line is already complete. The next step is to establish how the function progresses from one point to another. Does it follow a linear or nonlinear path (polynomial, logarithmic, etc)? Once this has been determined the points should be connected in this manor to create the guide line as shown in Figure 27d. The connection between Points A to B for instance is linear while Points E to D is logarithmic. If the stakeholder believes this is a good and accurate representation, the guide line becomes the design desirability function. If on the other hand the stakeholder does not believe this is a good and accurate representation, the stakeholder is free to modify the guide line, to create the design desirability functions as shown in Figure 27e, indicated by the solid black line.

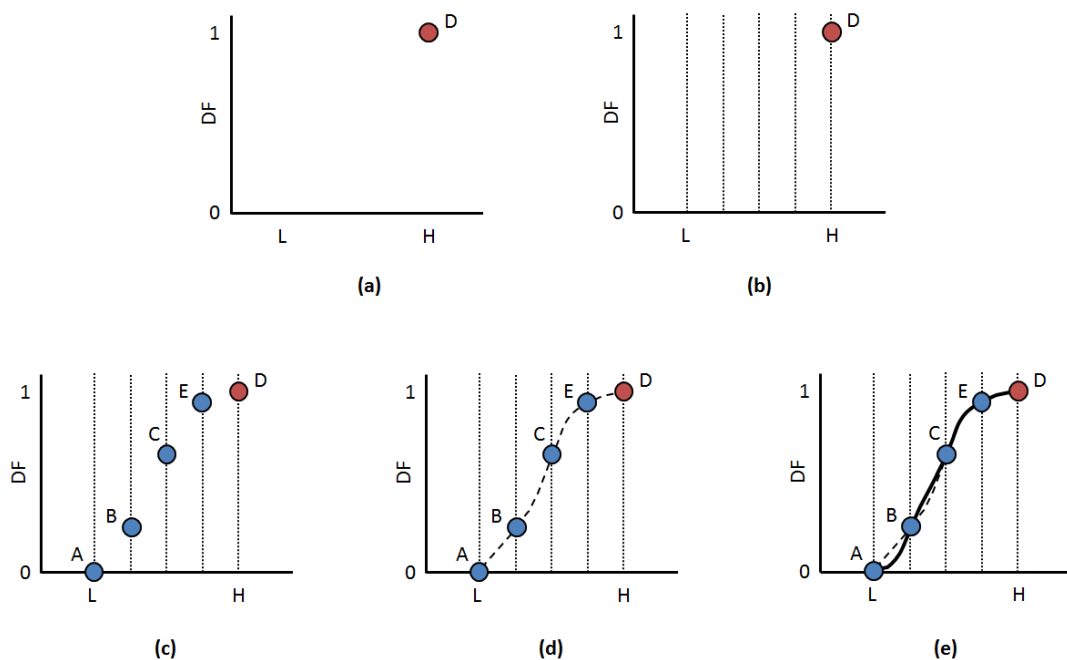


Figure 27 - A Systematic Approach To Creating Design Desirability Functions

After collecting all of the system level requirements and desirements, a review needs to be performed, to firstly verify that they are correct and secondly identify and resolve any potential conflicts. The results of this review may also identify that stakeholder is missing or not relevant to this system. If this is the case the process should return to step one with process only continuing when no conflict exists and all stakeholders are in agreement.

The final part of step 2 is to perform a function analysis similar to the current System Engineering process. Like the System Engineering process the functional analysis task is a very important activity within the Value Seeking System Design process as it bridges the gap between system level requirements and constraints and design synthesis. The purpose of a functional analysis is to identify all of lower level functions which the system must perform to achieve the system level requirements. This task may take much iteration to complete as the activity might highlight conflicts between functions which will have to be traded off or compromised to generate a viable solution. The major deliverable of the functional analysis will be the system functional architecture which arranges all functions in a logical and traceable manner.

Step 3 – Decompose and allocate requirements and desirements

Step 3 involves decomposing and allocating the system level requirements and desirements to component level. The task of decomposing and allocating requirements within the VSSD approach is the same process used within the SE technique. Decomposing and allocating desirements on the other hand is a little different. While the process follows the same principles (the summation of all child levels equals the parent level) instead of a single value being allocated, the process assigns a range of values and a desirability function which corresponds to the parent level.

Step 4 - Create subsystem models within physical architectures

The next step involves transforming the list of functions and the associated requirements and desirements into physical architectures which will enable the system to perform all of the stakeholder needs. In other words defining the system's various subsystems and components. Models of these parts should then be created to optimise the design.

Step 5 – Create system value function

The creation of the VSSD value function was presented in section 4.2 and will not be repeated here. The VSSD value function will be employed in a similar manner to the VDD surplus value equation; to evaluate the value of various design choices and the overall value of different systems.

Step 6 - Generate design concepts

This step uses the models created in step 4 to begin generating various design concepts. The goal is to find a solution which satisfies all of the elected requirements and desirements and provides the highest value to stakeholders.

Step 7 - Verify design meets requirements

When a concept is complete, the first step is to verify the design against the requirements. If the concept meets all of the requirements it is deemed acceptable and able to move to the step. If it is discovered that one or more of the requirements has been violated the design needs to be modified and rechecked before continuing on further. If it is not possible to find a solution which meets all of the requirements, the requirements are either modified with the acceptance of the stakeholders and the process of generating solutions begins again or the project is cancelled, if it is considered infeasible to correct given the available resources.

Step 8 - Verify Design Meets Desirements

Similar to step 7, this step verifies the design meets all desirements. If the concept meets all of the desirements it is deemed acceptable and able to move to the step. If it is discovered that one or more of the desirements has been violated the design needs to be modified. After modification the design must go back to step 7 to ensure that it still meets all requirements. If all requirements are passed, the concepts desirements are rechecked. If the design now passes both requirements and desirements, the design can move to the next step otherwise another modification is required before being rechecked. If it is not possible to find a solution which meets all of the requirements and desirements, either or both of them should be modified with the acceptance of the stakeholders and the process of generating solutions begins again or the project is cancelled, if it is considered infeasible to correct given the available resources. While it might seem desirement modification is the obvious choice here, this should not be assumed. Instead designers should seek clarification on what aspect to modify, with the outcome of these discussions recorded for traceability.

Step 9 - Calculate system value

At this stage the value score of the concept is established using the value model. The value model will give each concept a single value score which the designers will use in the next step to either reject or accept the design.

Step 10 - Optimal design

If the concept is the first concept to pass requirements and desirements, its value score becomes the baseline value score. Following the initial concept, the design team then begin to generate different concepts with the aim of improving this value score. If a new concept is created which passes both requirements and desirements but has a higher value score than the original concept, the new concept becomes the preferred design with its value

score becoming the new baseline value score. Concepts which are created and have a lower value score than the current baseline concept are rejected as they offer lower value to the stakeholders.

The VSSD optimisation process is therefore similar to the VDD technique. However unlike the VDD technique, the VSSD approach splits the solution space into acceptable and non-acceptable regions through its use of requirements and desirements, which is more feasible to optimise given project constraints. Selecting the highest value design within the acceptable region is therefore the optimal system as it will meet every stakeholder need while also providing them with the most value. Although this appears to create the same optimisation scenario as the SE technique, the use of desirements creates a non-rigid solution space to instead of a rigid one, creating a novel optimisation environment. Once the most valuable design has been determined the concept moves into the validation stage.

Step 11 - Validate the Design Satisfies Needs

The final step is design validation. Up until this point only design verification has taken place which ensures the concept passes both requirements and desirements. Validation though ensures the design satisfies the stakeholder need. If the stakeholders approve the design, no further design modifications are required and the design moves into later stages of design i.e. detail design, prototype development, etc before entering final production. However if the stakeholder need is not satisfied the requirements and desirements are updated and the design process is redone.

Although the steps have been outlined above as sequential and unidirectional, the process in reality is iterative and constantly being verified through feedback loops between the various stages.

To illustrate the differences between the SE, VDD and VSSD techniques, Figure 28 compares the steps within each approach. Note the SE and VDD flowcharts have been modified from Ref. [4] and Ref. [56] respectively. As Figure 28 shows the VSSD approach draws on elements currently used within the state of the art techniques (indicated by the arrows) but with key differences in how system needs are captured, how designs are evaluated and how the final design is selected (indicated by the green boxes); to create an innovate design process for developing complex systems.

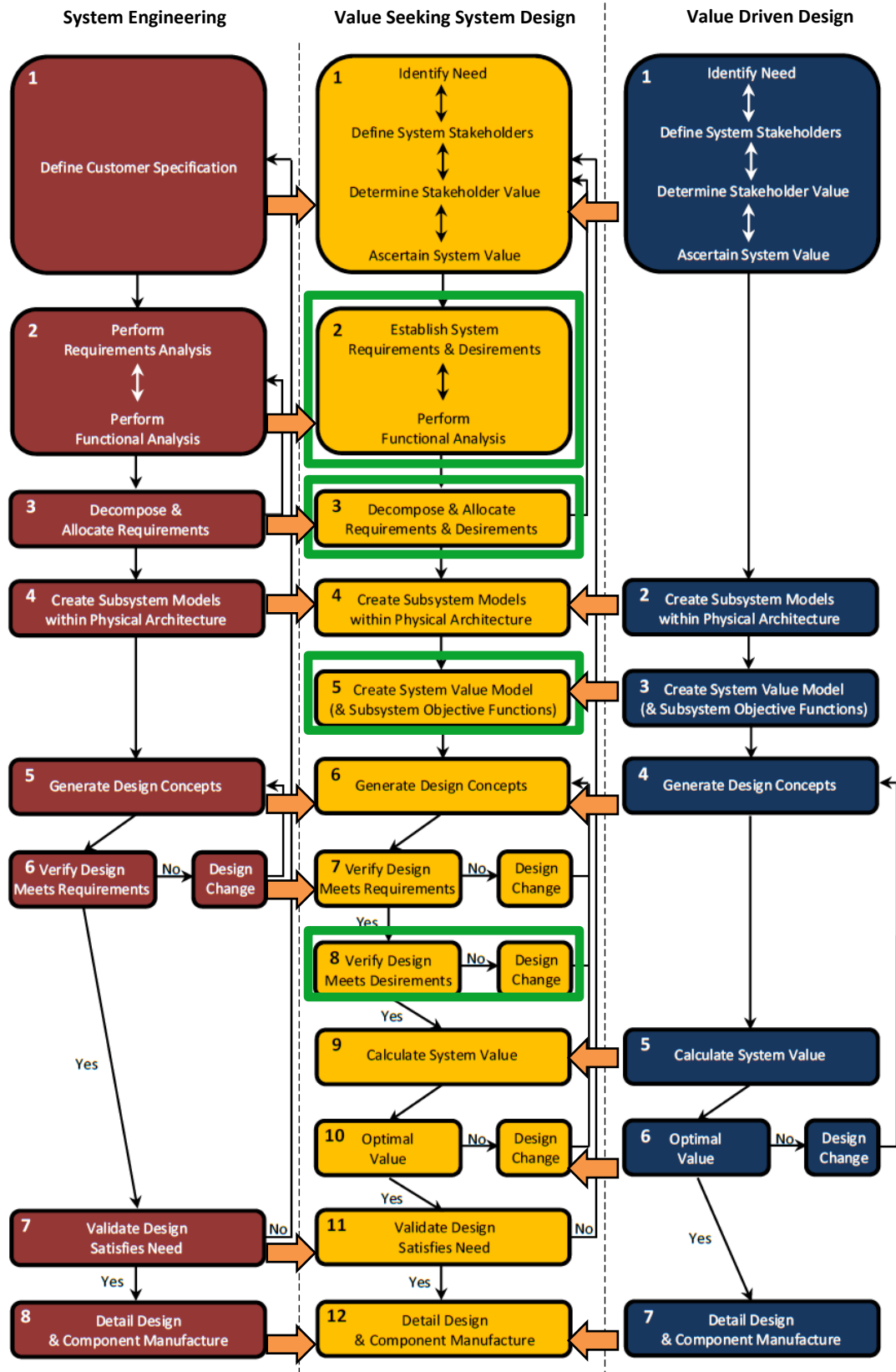


Figure 28 – Comparison Between The SE, VDD And VSSD Techniques

5.2 Summary

The aim of this chapter was to present a novel methodology capable of designing complex systems. By combining the new design elements introduced in Chapter 3 and 4 (i.e. desirements and the new value function) with elements already established within the current state of the art methods, this aim was achieved. Key differences in how system needs are captured, how designs are evaluated and how the final design is selected aims to retain the benefits associated with the current System Engineering and Value Driven Design techniques while simultaneously addressing their limitations.

The focus of the next two chapters is on benchmarking the Value Seeking System Design technique against the System Engineering and Value Driven Design methods. Chapter 6 provides an overview of the design problem and model utilised within this research to benchmark the VSSD technique while Chapter 7 presents the results of this study.

Chapter 6: Design Problem And Model Overview

In order to fully assess the Value Seeking System Design technique ability to create complex systems, a comprehensive modelling environment needs to be developed. This environment must create and seamlessly integrate not only the physics of the complex system, but also the full economic life cycle analysis of the system and the additional value-based metrics and calculations proposed in this research. This section of the report outlines the process which was conducted to create this comprehensive modelling environment and the process used to benchmark the proposed value technique against the traditional System Engineering and Value Driven Design approaches. To benchmark the new technique, a simplified design problem of a complex system is introduced. All three design methods will then be independently applied to solve it. The goal of this process is to find the best possible solution for the stakeholders by following the steps involved in each approach. The process of how each technique transitions from the stakeholders needs to final system will be demonstrated in the following chapter. The focus of this chapter is to introduce the design problem along with the comprehensive mathematical model developed as part of this research to assist in the decision making process. While the problem has been simplified for demonstration purposes, it still represents all the main challenges that would be incurred when developing a complex system. Notional operational values and constraints have also been included to give the process realism. These values, however, can easily be modified within the model to investigate different scenarios.

6.1 Design Problem

To test the feasibility of the new design approach and benchmark it against the current state of the art methods a simplified design problem was created. After much consideration it was decided that each approach would be used to develop a new 150 passenger aircraft. Aircraft are complex systems consisting of many subsystems, each with their own purpose but all working together to achieve one common goal of human flight. The example however has been simplified for demonstration purposes but it still represents all the main challenges incurred when developing a 150 passenger aircraft. The next sections outline the problem in more detail, stating the aircraft's design mission, operational area, utilisation, load factors and assumed configurations to simplify the design process.

6.1.1 Design Problem Overview

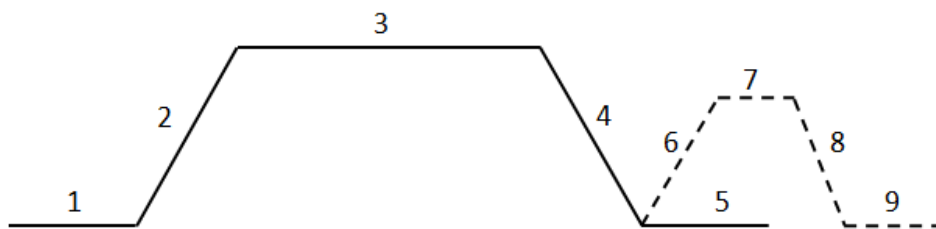
The first step in any design approach is to define the problem needing solved. In this study it is the development of a new 150 passenger commercial aircraft. Over the past 40 years, commercial aircraft manufacturers have evolved their designs with the aim of improving the designs performance and/or reducing the aircraft's operational costs rather than develop a completely new concept [144] i.e. the Airbus A300 family or the Boeing 737 family. To determine the target values for this research a review of existing 150 passenger aircraft was performed. The Airbus A320 and the Boeing B737-800 are currently the two most successful designs in the 150 passenger class with similar capacity and range. After reviewing these designs, the initial target values for the new aircraft were determined and are summarised in Table 5.

Table 5 – Target Values Of New 150 Passenger Aircraft

	Target Value	Airbus A320 [145] [146]	Boeing 737-800 [147] [148]
Design Range (nmi)	3,000	3,300	3,115
Cruise Altitude (ft)	37,000	39,000	41,000
Typical Cruise Speed (Mach)	0.76	0.78	0.785
Passenger Configuration (dual class)			
Number of First Class Passengers	12	12	8
Number of Economy Class Passengers	138	138	156
Price (\$ Million)	130	97	96
Cargo Container	LD3 - 45	LD3 - 45	N/A

6.1.2 Design Mission

The design mission of the aircraft will be typical of any commercial transport i.e. safely transport passengers between different destinations. A visual representation of mission segments the aircraft will fly between destinations is shown in Figure 29.



- | | | |
|-------------|------------------|----------------------------|
| 1. Taxi Out | 4. Descend | 7. Reserve Cruise & Lotter |
| 2. Climb | 5. Taxi In | 8. Reserve Descend |
| 3. Cruise | 6. Reserve Climb | 9. Reserve Taxi In |

Figure 29 – Visual Representation Of Mission Segments

The black solid line in Figure 29 represents a normal flight which includes taxi out, take-off, climb, cruise, descend, land and taxi in. All of these segments are assumed to remain constant within this study except for the cruise segment which represents the stage length of each sortie. It is assumed in this study that the designed aircraft will be utilised on multiple stage lengths with more details provided in the aircraft utilisation section. The dotted line however represents the reserve mission of climb, cruise/lotter (max. 250 nmi) and descend which is required by the FAA regulations to account for emergency scenarios.

FAA regulations will also limit the speed of climb and descent of the aircraft within this research with no attempt made to alter this or any other regulation which may be beneficial to certain stakeholders. For example a steeper descent may reduce the noise of a landing aircraft which would be beneficial and welcomed by any member of the public living or working close to the airport. More information on FAA regulations can be found at the FAA website [149].

6.1.3 Aircraft Utilisation

Within this study 10 flight ranges have been identified and are listed below in Table 6. All of the annual flight hours and stage lengths listed in Table 6 are notional and only meant to represent the envisaged operation of the aircraft being created for a potential airline. The stage length and the flight hours assigned to each stage length within Table 6 however can be easily modified to represent another operational study for the same or different airliner. For example Table 6 shows that the aircraft will be mostly utilised between the stage lengths of 500 nmi and 2000 nmi by the potential airliner. Another or the same airliner may wish to only fly the new aircraft on stage lengths above 2000 nmi. This is easily altered within the model with the effects this has on the design quickly established.

It is assumed the designed aircraft will have a maximum utilisation of 3800 hours which is typical for 150 passenger aircraft. [150] Instead of stating the number of flights per year in each stage length, the study splits the available hours between the different stage lengths to prevent penalisation of faster aircraft i.e. faster aircraft can perform more flights per year. Simply stating the stage lengths and annual flight hours however can be misleading to the operational use of the aircraft; as longer stage lengths naturally incur longer flight times. To assist visualise how the aircraft is utilised throughout this study, the approximant number of flights has been calculated for each stage length using the average cruise speed considered within this research (0.78 Mach), with the accumulation row representing the percentage of flights up to and including that stage length.

As this study includes aircraft which have varying design ranges, only the stage lengths which each aircraft is capable of flying will be analysed. If the aircraft is unable to fly a particular stage length because it exceeds the design range of that aircraft, the revenue and operational costs incurred for that range are both assumed to zero as the aircraft cannot perform this operation. For instance if the aircraft has the design range of 3000 nmi, it cannot fly the 3300 nmi stage length. As the 3300 nmi stage length is not possible, the design cannot generate any revenue for this stage but since it does not perform this flight no costs are incurred. Not being able to perform all stage lengths however does reduce the utilisation of the aircraft as the hours allocated to these stage lengths are not transferred to other feasible stage lengths. For instance if an aircraft is unable to fly the 3300 nmi because it has a design range of 3000 nmi, the 200 annual flight hours allocated for the 3300 nmi stage length (see Table 6), effectively reduces the utilisation of the aircraft to 3600 hours (3800 – 200) as these extra 200 hours are not reallocated to the stage lengths of 3000 nmi or lower. While this may not accurately reflect reality due to airliners always striving to maximise utilisation and non-flown sorties leading to aircraft out of operational position, it is assumed due to the envisaged operation of the aircraft, this underutilisation is minor and

all aircraft are where they are required to be regardless of non-flown sorties. If the envisaged operational use of the aircraft however was to change with more flights occurring at the longer stage lengths this assumption may no longer be valid but at present the vast majority (93%) of all flights occur below 2700 nmi.

Table 6 – Envisaged Aircraft Utilisation

Stage Length (nmi)	250	500	750	1000	1500	2000	2500	2700	3000	3300
Annual Flights Hours	60	170	340	510	600	620	520	460	320	200
Approx. % of Flights	5	10	15	19	15	13	8	8	4	3
Cum. % of Flights	5	15	30	49	64	77	85	93	97	100

6.1.4 Aircraft Operational Region

The latest market outlook by Boeing [151], suggests that the world fleet is expected to double by 2033 with the single aisle aircraft increasing its global dominance to nearly 70%. The report also highlights the growing demand of air travel with emerging markets (Asia Pacific) growing faster than more established markets of Europe and North America. [151] This research however will focus its attention on the established markets of Europe and North America as this is where the new aircraft will be assumed to operate. Table 7 outlines the envisaged operations of the new aircraft along with the expected delays within each region.

Table 7 – Envisaged Airline Operations

Stage Length (nmi)	250	500	750	1000	1500	2000	2500	2700	3000	3300
Flight Op. EU %	70	60	60	60	50	50	50	50	50	50
Flight Op. US %	30	40	40	40	50	50	50	50	50	50
EU Delay (Short/Long)	9:1	9:1	8:2	8:2	8:2	8:2	8:2	8:2	8:2	8:2
US Delay (Short/Long)	9:1	9:1	9:1	9:1	8:1	8:2	8:2	8:2	8:2	8:2

The operational region (either EU or US) and anticipated delay for each stage length is required to calculate the delay and cancellation costs. In this study it is expected that 90% of all 500 nmi flights operating within the EU will have a short delay (up to 15 mins behind schedule) with the remaining 10% either having a longer delay or being cancelled. Similarly it is expected that 80% of all 2000 nmi flights operating within the US will have a short delay (up to 15 mins behind schedule) with the remaining 20% either having a longer delay or being cancelled. Note: All values stated in Table 7 are notional and easily updated within the model.

To operate the new aircraft in and out of the envisaged airports, it must be compatible with existing airport infrastructure and pass all aviation regulations. As the aircraft is to be similar to the Airbus 320A and the Boeing 787-800, it is expected that the new aircraft will have a type code of C-III which will allow it to operate in and out of the same airports as the current designs do.

6.1.5 Load Factors

Load factors are an important aspect within the profitability of aircraft with increased load factors representing additional customers and hence profit. To calculate the passenger load factor Equation 22 is used.

$$\text{Load Factor} = \frac{\text{Passengers Served}}{\text{AvailableSeats}} \quad (22)$$

Both the Airbus A320 [145] and the Boeing B737-800 [148] have two possible seating configurations, either dual or single. This research however will focus solely on the dual seating configuration.

It is assumed that the designed aircraft will have 12 first class passenger seats with 9 first class passengers on every flight. The first class load factor for every flight is therefore 75%.

The economy load factor however is variable due to study including aircraft with varying passenger numbers. While the first class passenger seats is fixed at 12, to increase the capacity of the aircraft the number of economy seats alters. Assuming a constant economy passenger number would favour a design with less economy passenger seats as the aircraft would be utilised more efficiently. To determine the economy load factor of the aircraft a Monte Carlo simulation was used to generate economy passenger demand assuming a normal and triangular distribution. The results of the Monte Carlo simulation are shown in Figure 30.

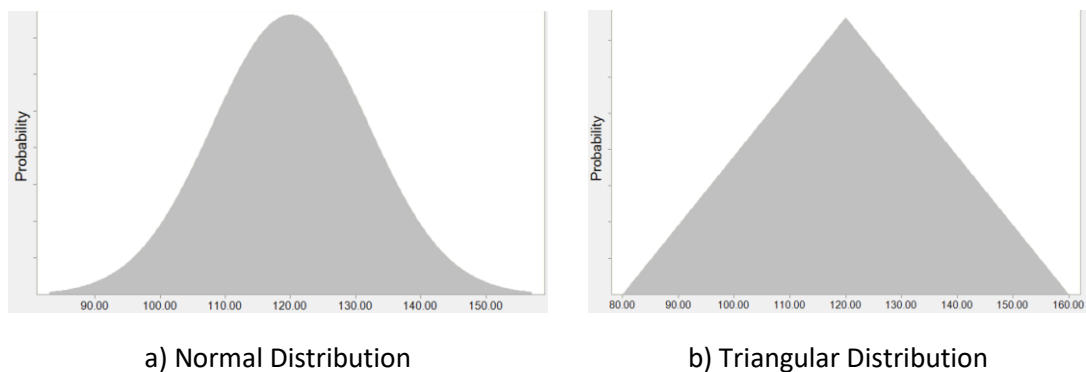


Figure 30 – Monte Carlo Simulation For Economy Passenger Demand

These values were then fed into an Excel model to determine the economy load factor based on the number of economy seats available within the design and the demand. If the demand exceeded the number of available economy seats, the load factor was set to one with the design unable to take advantage of the extra demand. Table 8 demonstrates this process of varying passenger demand, aircraft capacity, passengers served, load factor and passengers not served.

Table 8 – Economy Load Factor Examples

Economy Passenger Demand	Aircraft Capacity	Passengers Served	Load Factor	Passengers Not Served
90	120	90	0.75	0
90	140	90	0.64	0
90	156	90	0.58	0
140	120	120	1.00	20
140	140	140	1.00	0
140	156	140	0.90	0

Figure 31 represents the economy load factor based on passenger demand (assuming a normal and triangular distribution) and available economy seats. The average load factor which is based on average of the normal and triangular distribution is also shown on Figure 31 and was used as the economy load factor within the study.

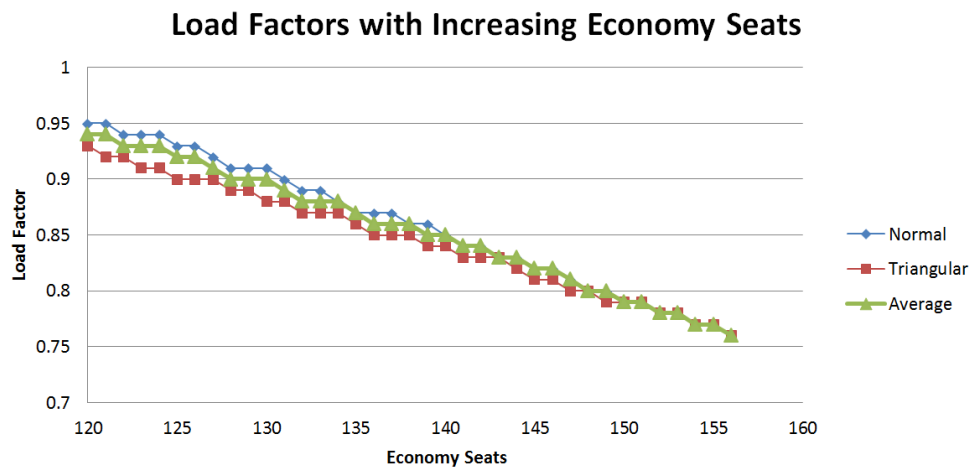


Figure 31 – Assumed Economy Load Factors Based On Aircraft Capacity And Demand

6.1.6 Aircraft configurations

Aircraft can be designed using a variety of different configurations. This study however applies the following assumptions to reduce the number of design possibilities.

- 1) The aircraft will consist of a conventional wing and tail design.
- 2) The cross section of the fuselage will be circular.
- 3) The wing would be low in design, fixed and have a constant dihedral angle.
- 4) The aircraft will carry at least 4 LD3-45 cargo boxes.
- 5) Each passenger weighs 165 lb.
- 6) Each passenger will have 44 lb of hold baggage.
- 7) All aircraft will be designed to have an operational life of 25 years.
- 8) All fuel will be carried within the wings of the wings of the aircraft.
- 9) The cabin layout will have a seating configuration of 2x2 for first class passengers and 3x3 for economy class passengers.
- 10) The overhead bin will be designed to allow each passenger to store one 22x18x10 inch bag.
- 11) The power plant of the aircraft will consist of two CFM International CFM56-3 engines and be placed under the wings. While this engine was used on the classic Boeing 737-400, the predecessor of the 737-800, the data for this engine was the most up to date and publically available engine during this study. As this engine is less efficient than the latest models, the regulations on both noise and emissions have been adjusted accordingly. This assumption is acceptable as all designs will be subjected to the same regulation regardless of the technique used to develop the aircraft.

The next section provides a detailed overview of comprehensive modelling environment created within this research. Its purpose is to assist in the decision making process, regardless of the design methodology being employed.

6.2 Research Model

To assist benchmark the proposed technique an aircraft model was created and is introduced this section.

6.2.1 Model Creation

The model consists of four key elements; FLOPS, ALCCA, Passenger Space and Surplus Value all of which were linked using Microsoft Excel and Visual Basic software. The FLOPS [152] and ALCCA [153] programs are two programs already well established within industry and academia for primarily aircraft design and were used within this model to predict the performance, sizing and life-cycle costs of the different conceptual aircraft. Both the passenger space model and the surplus value model were created within Microsoft Excel and were built to predict the cabin space for each passenger and the surplus value of each concept. The surplus value model was validated using published research and the cabin space was validated using 3D modelling. A simplified overview of the created model is shown in Figure 32 which highlights how the model's key elements interact with each other and how certain results from one element become inputs for other elements. For instance results from the FLOPS and ALACCA model are feed into the Surplus Value Model to determine the design's surplus value. Each of the four elements will now be discussed.

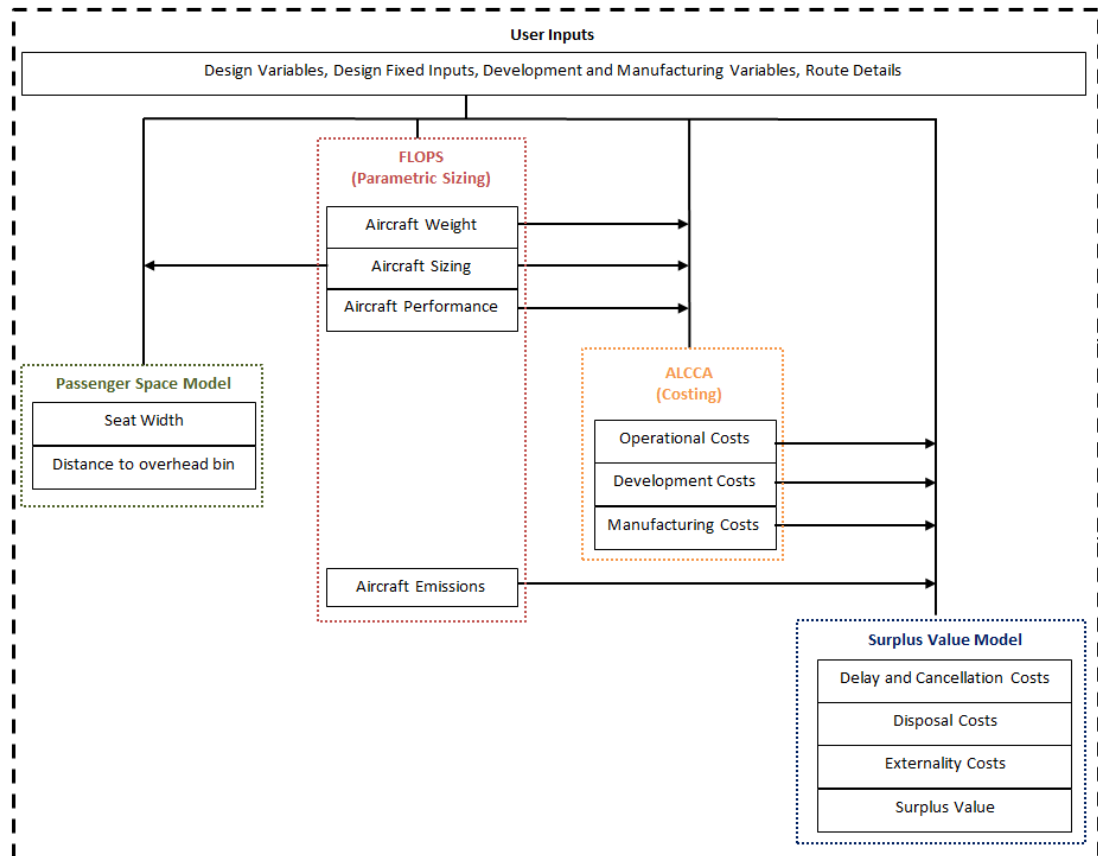


Figure 32 – Overview Of Research Model

6.2.1.1 FLOPS (FLight OPTimisation System)

The FLOPS program was developed by the NASA Langley Research Centre to assist in the preliminary design of different aircraft configurations. [152] The name FLOPS is an acronym meaning FLight OPTimisation System. Although the program has the ability to size and predict the performance of many different types of aircraft, this study focused on the design of a 150 passenger commercial transport aircraft.

The program itself is relatively simple to use and has become a reliable tool within industry and academia for its ability to quickly analyse and evaluate conceptual and preliminary designs. To run a simulation the user creates an input file (.in) which is then fed into the FLOPS program via the command prompt. The input file is a basic text file, containing a list of variables which are organised into name lists for easy identification and modification.

The variables in the names lists are then modified to set the mission profile as well as place any restrictions on the design. These include but not limited to cruise Mach number, design range and passenger number as well as approach speed and maximum field length. For further information on how to generate these input files the manual should be consulted. [152] A detailed description of what each variable is and its default value can also be found in the manual along with solutions to common run time errors; usually caused by poorly created input files. To save time and reduce the complexity of the input file only variables which differ from the default value or variables which are required but have no default value must be entered into the FLOPS input file; as the FLOPS program will automatically use the default value unless it is over written by the user. To configure the input file for this study's, the initial file's parameters were based on a generic 150 passenger aircraft using the information found in Ref [154].

FLOPS is a multidisciplinary system of computer programs and consists of nine primary modules including weights, aerodynamics, engine cycle analysis, propulsion data scaling and interpolation, mission performance, take-off and landing, noise footprint, cost analysis (not used in the study as the ALCCA was used instead) and program control. [152] The weight module uses empirical equations to predict the weight of each item within the group weight statement. Similarly the aerodynamics module uses a modified version of the empirical drag estimation to calculate drag polars for performance calculations. Once this data is created FLOPS uses this information along with the propulsion data supplied within the engine deck to calculate the mission performance of the aircraft; including its take-off and landing performance and noise profile (FAR sideline and flyover noise). The results of the simulation are exported from the program within an out file (.out) which is a basic text file displaying the information requested by the user in a readable format. Originally FLOPS was created using FORTRAN based code however the version used in this research had already been compiled (with a G95 compiler) into an executable file, version number v6.03.

6.2.1.2 ALCCA (Aircraft Life Cycle Cost Analysis)

To predict the aircrafts life-cycle costs, FLOPS was linked to the Aircraft Life Cycle Cost Analysis (ALCCA) program which was originally developed by NASA Ames. [153] The Aerospace System Design Laboratory (ASDL) out of the Georgia Institute of Technology, however, has enhanced this tool adding new features to forecast all life cycle costs associated with commercial transport aircraft. Economic outputs such as Total Operating Costs (TOC) and aircraft acquisition costs can be calculated using this program quickly determining the important financial aspects of the aircraft which is not available in FLOPS.

The ALCCA tool uses the geometric, weight and propulsion characteristics of the aircraft created in the FLOPS program along with economic assumptions and manufacturing considerations to perform a complete economic assessment of the concept design. Like FLOPS, ALCCA comprises a list of variables within names lists which are similarly modified to run different simulations. Modification of certain input variables was required to accommodate the ALCCA program within the FLOPS program but these are easily found within the ALCCA manual along with the description of each variable. The version of ALCCA used in this study was v6.03 which had already been integrated into the original FLOPS program (v6.03) meaning only one input file was required. As FLOPS and ALCCA are integrated; the economic results of the simulation are included within the one results file.

6.2.1.3 Passenger Space Model

The passenger space model was created by the researcher using Microsoft Excel to determine the space available to each passenger given the particular geometry and cabin layout of the concept design. A visual representation of the passenger space model is shown below in Figure 33 highlighting the design variables considered within the model.

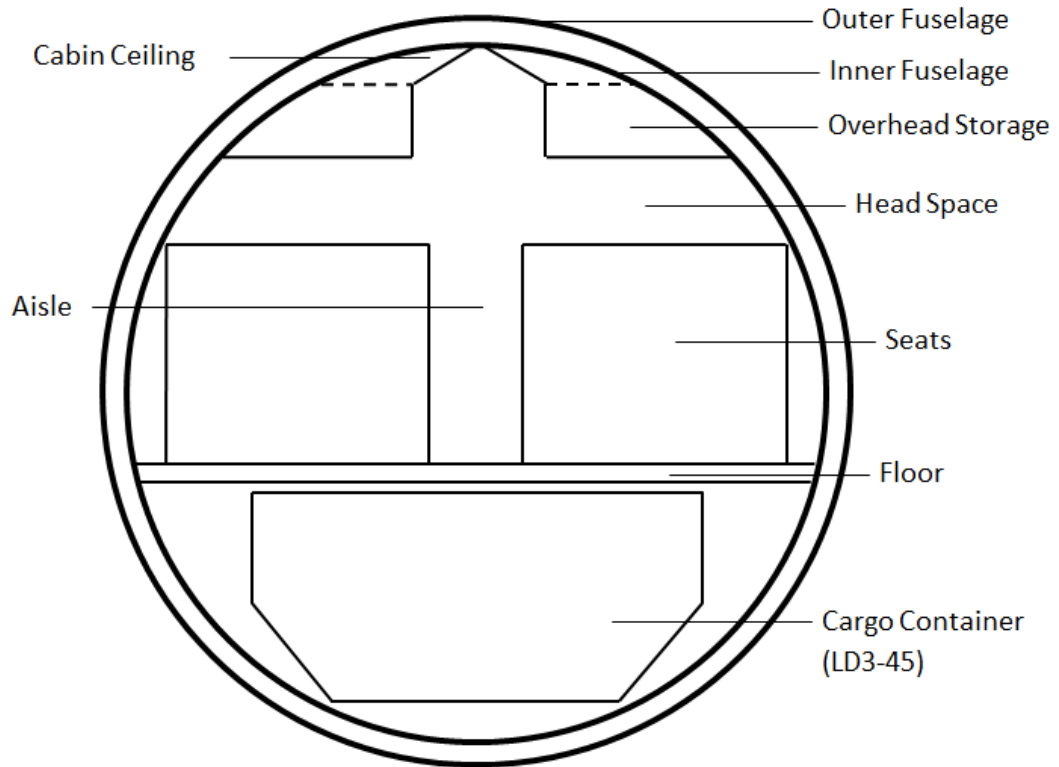


Figure 33 – Visual Representation Of The Passenger Space Model

It was assumed in section 6.1.6 that every passenger would be able to store a 22x18x10 inch bag in the overhead storage bin and the aircraft would be capable of carrying LD3-45 containers within its fuselage. The model assumes that the unit load devices (i.e. the LD3-45 containers) are entered into the lowest possible point of the fuselage (with an offset to accommodate mounting points) regardless of the fuselage width with the floor and seats being placed directly above.

The seats were assumed to be 4 foot in height from the floor to the top of the head rest. The aisle width for every concept was assumed to be 20 inches with the storage bins set back 2 inches from the aisle. The aircraft fuselage was assumed to be 6 inches thick with the floor being 4 inches in depth. All of these assumptions however can easily be modified within the model if so desired by the user.

The two key outputs of the passenger space model are the seat width and the head space available to each passenger. Since the overhead storage space must be capable of carrying a 22x18x10 inch bag for each passenger, the model calculates the available head space between the top of the seat and the overhead storage space rather than fail to fulfil this assumption. The model has been designed to automatically change the orientation of the bag within the overhead storage to maximise the head space for the passenger.

6.2.1.4 Surplus Value Model

Although ALCCA could generate the operating and acquisition costs for each design it lacked the ability to calculate a design's surplus value. To achieve this, a new model was created by the researcher which combined the results from ALCCA along with the other currently unaccounted costs (emissions charges, delays and cancellations costs) and the revenue potential of the design.

Revenue

To calculate the revenue potential of each design the average ticket price for each stage length listed within the typical missions needed to be determined. This however was not an easy task as there are many factors which can influence the price of air travel. These include but are not limited to the aircraft model flown, airline model, route flown, salaries, fuel costs and airport charges. Airfares are also driven by the principle of supply and demand and are more sensitive to price fluctuation than any other transport industry (train, bus, etc). It is also acknowledged that the results within this study may be biased due to searches performed and routes monitored. The results therefore should only be used as a guide but can easily be modified within the model if desired by the user.

The stage length vs price study was conducted between November 2013 and April 2014 using data acquired from both Skyscanner and Google Flights search engines. The results

focused on flight routes within Europe and America as well as transatlantic flights between the two continents. Prices for flights six months in advance to flights the next day were all included to gauge an average price for each stage length. One piece of hold baggage (weighing 20kg or 44 lbs) was also included within the pricing of each stage length as it was assumed in section 6.1.6 that every passenger would have one piece of hold baggage. The results of the study can be found in Figure 34 where each point represents the average price of each stage length for economy class.

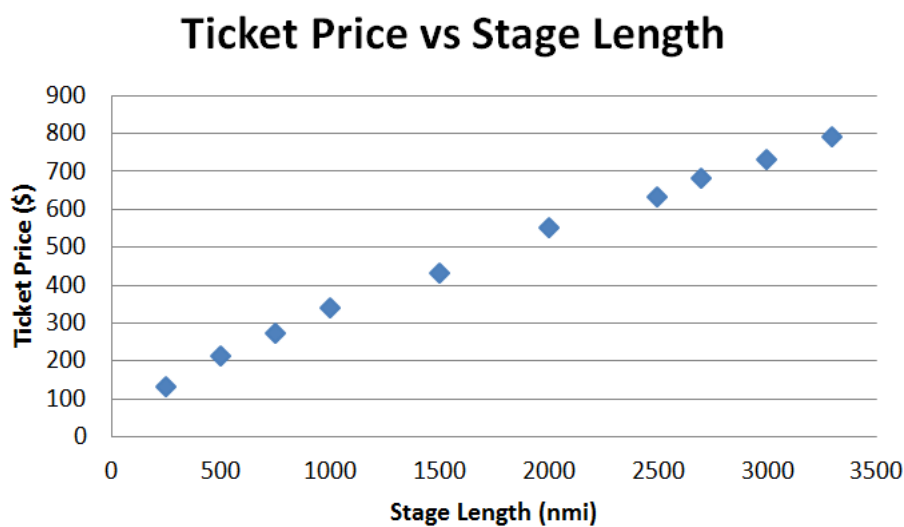


Figure 34 – Airfare Vs Flight Distance

A similar but not as extensive study was performed to calculate the first class cost of each stage length. The results indicated that the average stage length was approximately 3.5 times the price of economy with some airlines charging up to 5 times depending on the flight. This factor may seem high initially but comparing the seat layout in Figure 35, 12 first class passengers occupy the same space as 24 economy class passengers assuming a 40 and 30 inch seat pitch and a 2x2 vs 3x3 cabin layout respectively. Therefore to achieve the same revenue potential for the same cabin space requires the first class ticket to be double the economy ticket.



First Class (2x2 Layout, 40 inch pitch)

Economy Class (3x3 Layout, 30 inch pitch)

Figure 35 – Aircraft Seating Arrangement

Extra space however is only one of numerous benefits first class passengers pay for, which extend beyond the service received on board the aircraft. In general the first class flight experience is more luxurious than the economy counterpart receiving a more comfortable seat, amenities, an airhost shared between less passengers, gallery and toilet with special check-in and security zones at certain airports. For all of these reasons a 3.5 factor was applied to each of the economy stage lengths to calculate the price of the first class ticket.

Delay and cancellation costs

The delay and cancellations costs refer to the costs incurred by an airliner due to a flight delay or cancellation. The costs incurred are both location and time dependant. To calculate these costs, the model developed by Abdul Qadar Kara, et al. at George Mason University [119] was employed and incorporated within this research model. The model developed at George Mason University is an additive general model combining the costs of three different segments; namely gate, taxi and en-route to calculate these costs.

Externality Costs

The externality costs are the costs incurred by the airliner due to negative societal good of operating the aircraft. The costs include the emission charges, airport charges and other taxes. In this research it is assumed that all airport charges are equal (\$2,000) as well as the cost per tonne of CO₂ emitted (\$132).

Disposal Costs

The disposal cost refers to the costs incurred by the airliner to retire the aircraft at the end of its operating life. Some airline operators however many opt to sell their aircraft before they reach this stage to avoid this cost turning this inevitable expense into revenue potential. This study however assumes that each concept will not be resold.

To calculate the disposal cost of each concept this research follows the estimation provided by Roskam [118] and Ghorbany and Malaek [121] which indicates that an aircraft's disposal cost is approximately 1% of an aircraft's lifecycle costs. While this 1% estimation value is based on traditional aircraft design and expected to change as aircraft designs become more complex and incorporate more advanced materials, a static 1% value was used throughout this study regardless of the composite composition of the concept.

6.2.1.5 Evaluation Of Each Design Concept

In addition to the four elements already discussed, the model has been developed to automatically evaluate every design concept according to the evaluation criteria of each design methodology. To achieve this, the designer enters the evaluation criteria for each technique i.e. SE, VDD, VSSD when setting up the model and has been designed to be easily modified if required. In the case of System Engineering technique, the designer enters the complete list of requirements into the "System Engineering Requirement" section of the model. Once a design has been generated, the model then uses this list of requirements to determine if the concept is acceptable or not. The model indicates which requirements the concept passes or fails by displaying "Pass" or "Fail" beside each requirement. If the concept passes the complete list of requirements the concept ID (the concept's unique identifier) turns green to indicate an acceptable design has been generated otherwise it turns red indicating an unacceptable concept has been generated because at least one requirement has failed. A similar process occurs for the Value Driven Design and Value

Seeking System Design techniques but each design concept is also automatically ranked from highest to lowest value according to the value function used within that approach. The major benefit of this automation was time taken to evaluate each design concept was significantly reduced (from minutes to milliseconds) while also minimising human error.

6.2.2 Model Assumptions

Tables 9, 10, 11 and 12 list the model assumptions used throughout this study. The year is assumed to be 2009 with all economic analysis being performed in US Dollars.

Table 9 – ALCCA Economic Assumptions

	ALCCA Input	Description	Value
Rates	API	Average Annual Inflation Factor (%)	7.5
	RE	Engineering Labour Rate (\$/hr)	89.68
	RT	Tooling Labour Rate (\$/hr)	54.68
	RL	Maintenance Labour Rate, (\$/hr)	19.5
Spares	AFSPAO	Airframe Spares for Production (%)	6
	ENSPAO	Main Engine Spares for Production (%)	23
Crew	AI11	Passengers per Flight Attendant Ratio, First Class	12
	AI12	Passengers per Flight Attendant Ratio, Economy Class	50
Financing	DWNPYM	Down Payment (%)	0
	RINRST	Rate of Interest for Financing (%)	10
Depreciation	DEPLIFE	Depreciation period	25
	RESVVL	Residual Value at end of Economic Life (%)	10

Note: manufacturing costs are inflated from the baseline dollars of 1970 at a rate of 7.50% per annum.

Table 10 – Additional Economic Assumptions

Variable Name	Value
CO ₂ Emission Charge Per Ton (\$)	132
First Class Ticket Cost Multiplier (-)	3.5
Disposal Factor (% of LCC)	1
Airport Take-Off and Landing Charge (\$)	2000
Fleet Size (-)	1500
Fuel Price (\$/gal)	3
Aircraft Economic Life (Years)	25

Table 11 – Summary Of Envisaged Airline Operations And Pricing Structure

Range (nmi)	250	500	750	1000	1500	2000	2500	2700	3000	3300
Economy Ticket Price (\$)	130	200	270	330	430	540	630	670	730	790
Annual Flights Hours	60	170	340	510	600	620	520	460	320	200
Flight Op. EU %	70	60	60	60	50	50	50	50	50	50
Flight Op. US %	30	40	40	40	50	50	50	50	50	50
EU Delay (Short/Long)	9:1	9:1	8:2	8:2	8:2	8:2	8:2	8:2	8:2	8:2
US Delay (Short/Long)	9:1	9:1	9:1	9:1	8:1	8:2	8:2	8:2	8:2	8:2

As the percentage of composites within the wing and body could vary within this study, the learning curves were automated to reflect this within the economic analysis. It was assumed that both the wing and body of the aircraft would be split between composite and aluminium materials only meaning a percentage increase in composites would incur a similar percentage decrease in aluminium and vice versa. The FCOMP (Decimal fraction of amount of composites used in wing structure) input parameter within the FLOPS program was used to define the percentage of aluminium and composites within the wing and body, and consequently the learning curves (LC) for manufacture and assembly of these parts. It was assumed that the first 200 production units manufactured would be based on the 1st lot learning curve with the remaining based on the 2nd lot learning curve. Table 12 displays

the material assumptions made within this study for both with wing and body of the aircraft as well as the learning curves based on the FCOMP value. Note: Table 12 values were based on discussions with experienced FLOPS and ALCCA users and learning curve data within Ref [155] since public data was not available.

Table 12 – Material Assumptions And Learning Curve Based On FCOMP

FCOMP	PWINGAL	PWINGCO	PWBODYAL	PWBODYCO	1st Lot LC (%)	2nd Lot LC (%)
0.0	1.00	0.00	1.00	0.00	80.0	78.0
0.1	0.95	0.05	0.97	0.03	80.2	78.2
0.2	0.90	0.10	0.94	0.06	80.4	78.4
0.3	0.85	0.15	0.91	0.09	80.6	78.6
0.4	0.80	0.20	0.88	0.12	80.8	78.8
0.5	0.75	0.25	0.85	0.15	81.0	79.0
0.6	0.70	0.30	0.82	0.18	81.2	79.2
0.7	0.65	0.35	0.79	0.21	81.4	79.4
0.8	0.60	0.40	0.76	0.24	81.6	79.6
0.9	0.55	0.45	0.73	0.27	81.8	79.8
1.0	0.5	0.50	0.70	0.30	82.0	80.0

Note: FCOMP = Decimal fraction of amount of composites used in wing structure
PWINGAL = Fraction of Aluminium Materials Used in the Wing
PWINGCO = Fraction of Composite Materials Used in the Wing
PWBODYAL = Fraction of Aluminium Materials Used in the Body
PWBODYCO = Fraction of Composite Materials Used in the Body
1st Lot LC (%) = Learning Curve Factor for first lot
2nd Lot LC (%) = Learning Curve Factor for second lot

6.2.3 Metrics

This section provides a brief overview of the metrics utilised in this study to describe each design concept. The metrics are classed into performance, economic and social metrics and

are representative of system characteristics and constraints commonly encountered during aircraft design.

6.2.3.1 Performance Metrics

Landing Field Length

Landing field length is defined as the distance horizontally from the point at which the aircraft is 50 feet above the earth's surface to the point at which the aircraft is brought to a complete stop. The FAR landing field length however is 66.7% longer than this to account for any irregularity (weather conditions etc) in the landing procedure. [156] This metric is directly related to the approach velocity, a higher velocity requires a longer runway to safely decelerate and stop the aircraft. Aircraft are only allowed to land at airports where the length of the runway is greater than the aircraft's FAR field length.

Take-off Field Length

Take-off field length is defined as the distance travelled horizontally by the aircraft from the point which the take-off is initiated to the point at which the aircraft is at an altitude of 35 feet. [157] The FAR take-off field length, however, considers engine failure and is therefore slightly longer. It is often seen as a critical design constraint as if the runway is too short the aircraft cannot take-off with full fuel or payload which may compromise the aircraft's use and/or economics. The take-off field length is greatly affected by the aircraft's wing area and engine thrust, increasing either reduces required field length.

Approach Speed

Approach speed is the minimum speed required to safely control the aircraft during landing and therefore important to passengers, crew and airport personnel. It is based on the stall speed of the aircraft multiplied by a safety factor, which in the case of a commercial aircraft is 1.3. [158] To minimise the stall speed control surfaces may be employed.

Number of Flights per Year

Number of flights per year is the total number of flights performed by the aircraft in one year. It is directly related to the operational use of the aircraft, its design range and the cruise speed of the aircraft.

Take-Off Gross Weight (TOGW)

Take-off gross weight (TOGW) is the total weight of the aircraft at the beginning of a specified mission. It is closely related to the economics of an aircraft, especially operation costs.

Operating Empty Weight (OEW)

Operating empty weight (OEW) is similar to take-off gross weight but excludes usable fuel and payload of the specified mission.

6.2.3.2 Economic Metrics

Economy Passenger Load Factor

Load factors are an important aspect within the profitability of aircraft as they are a measure of how much the aircrafts load carrying capacity is being utilised. An increase in load factor represents additional customers which will be accompanied by increase in profit and to a lesser extent and increase in operating costs.

Profit Per Year

Profit per year is the total profit generated by the aircraft within one year. It is related to the operational capability of the aircraft including the revenue generation and all costs incurred during operation.

Total Research, Development, Testing and Evaluation Costs (RDT&E)

Research, development, testing and evaluation costs are all the costs incurred by the manufacture to research and develop the aircraft fleet as well as any costs incurred when testing and certifying the design.

Total Manufacturing Cost

Total manufacturing cost is the total cost incurred to build and assemble all of the required aircraft. Incorporating advanced materials into the design of the aircraft can push the cost of manufacturing upwards due to steeper learning curves, increased processing/raw material costs and the need to develop new jigs to assemble the aircraft.

Lifecycle Costs

The lifecycle cost of an aircraft is the total cost, including both recurring and non-recurring costs, incurred over the full life span of the aircraft. Traditionally aircraft with low life-cycle costs are preferred over aircraft with higher life-cycle costs as they cost less to own, operate and dispose of.

Aircraft Price

Aircraft price is the total cost which an airline must pay to own the aircraft from the manufacturer.

Disposal Cost

Disposal cost is the total cost to discard the aircraft safely at the end of its operational life. Costs include storage, disassembly, recycling and/or dumping. While it is possible to generate money from recycling or selling the aircraft before the end of its operational life this was not considered within this study.

Direct Operating Costs per Available Seat Mile (DOC/ASM)

Direct operating costs per available seat mile (DOC/ASM) is the total costs related to flying the aircraft (e.g. crew wages, fuel, etc) divided by the number of available seats multiplied by the number of flown miles. It is an important ratio used by management to determine the cost of transporting each available seat per mile.

Indirect Operating Costs per Available Seat Mile (IOC/ASM)

Indirect operating costs per available seat mile (IOC/ASM) is similar to DOC/ASM but is the total costs incurred by the airline when not flying the aircraft e.g. admin, terminal costs etc.

Environmental Costs

Environmental costs are the total charges in the form of taxes due to the environmental damage incurred for operating the aircraft. Noise and CO₂ emissions are the two most common taxes applied to aircraft. The surplus value equation classifies the environmental costs as externality costs.

6.2.3.3 Social Metrics

Social metrics consider how a system's operation effects, interacts and/or is perceived by society. Passenger comfort and emissions are two high profile examples within aircraft design today and is the reasoning behind these social metrics being incorporated within this study.

Seat Pitch

Seat pitch is defined as the distance between a point on one seat and the same point on the seat in front of it. Increasing seat pitch can provide more legroom and therefore comfort to passengers. Legroom though is affected by the thickness of the seat back.

Seat Width

Seat width in this study is defined as the breadth of a seat, including the arm rests. Similar to seat pitch increasing seat width increases the level comfort for the passenger as there movement is less restricted.

Head Space

Head space in this study is defined as the distance between the top of the seat and the overhead storage bin.

Aircraft Flyover Noise

Aircraft flyover noise is the noise level of an aircraft when flying overhead. It is measured under the departure climb path 6,500 metres from start of roll. [159]

Aircraft Side-Line Noise

Aircraft side-line noise is the noise level of the aircraft measured 450 metres from the runway centreline at the point where the noise level after lift-off is greatest. [159]

Emissions of Oxides of Nitrogen (NO_x)

NO_x refers to the emissions of nitrogen oxides, including nitrogen monoxide (NO) and nitrogen dioxide (NO₂). Aircraft regulations are requiring a reduction in NO_x emissions due to the environmental damage its causes both on the ground and in the air. In this study NO_x per year and NO_x/ASM is considered. NO_x per year is the predicted total emissions of nitrogen oxides emitted during the envisaged operation of the aircraft while NO_x/ASM is the predicted emissions of nitrogen oxides per available seat mile.

Emissions of Carbon Dioxide (CO₂)

CO₂ refers to the emissions of carbon dioxide (CO₂). Aircraft carbon dioxide emissions are directly related to fuel burn, with each kilogram of fuel being burnt creating 3.16 kg of carbon dioxide. CO₂ emissions within this study will therefore be calculated by firstly determining the fuel burn per available seat mile in kilograms and then multiplying the results by a factor of 3.16. [160] Similar to NO_x aircraft regulators are requiring a reduction in CO₂ emission to provide a cleaner method of travel and to also reduce the effects of climate change. In this study CO₂ per year and CO₂/ASM is considered. CO₂ per year is the predicted total emissions of carbon dioxide emitted during the envisaged operation of the aircraft while CO₂/ASM is the predicted emissions of carbon dioxide per available seat mile.

6.4 Summary

The aim of this chapter was introduce a simplified design problem which would be used to benchmark the purposed Value Seeking System Design technique against the current System Engineering and Value Driven Design approaches. After much consideration it was decided that the design problem would be the development of a new 150 passenger aircraft comparable to the Boeing 737 or the Airbus A320.

To assist in this process a mathematical model of the design problem was created and also introduced in this chapter. The model was developed using Microsoft Excel and Visual Basic software and consisted of four key elements: FLOPS, ALCCA, Passenger Space and Surplus Value. To minimise human error during the evaluation stage, the model automatically evaluates all design concepts against the evaluation criteria entered for each design methodology. The list of modelling assumptions used during this study can be found at the end of this section.

The chapter concluded with a brief overview of the system metrics utilised within this study to describe each concept.

The focus of the next chapter is to present the results of each technique before comparing them. It is envisaged by completing this task that the research questions and objectives listed in chapter two will be answered.

Chapter 7: Discussion & Results

The purpose of this chapter is to compare the results obtained by using the System Engineering, Value Driven Design and Value Seeking System Design techniques. To achieve this, all three approaches will be independently used to develop a range of design concepts with the overall aim of providing the “best” solution for the design problem introduced in chapter 6 i.e. the development of a commercial aircraft similar to the Airbus A320 or Boeing 737-800. To aid in this process the aircraft model created and outlined in chapter 6 will be used extensively throughout this task. The first technique to be applied will be the Systems Engineering, followed by Value Driven Design and finally the Value Seeking System Design technique. The chapter begins by providing an overview of how each methodology transforms the information outlined in Chapter 6 into the required format to solve the design problem. Once this task is complete, a comparison between all three approaches is performed to highlight the benefits or limitations of each approach, and draw conclusions about the utilisation of each methodology.

7.1 The SE, VDD and VSSD Approach To The Design Problem

This section demonstrates how each methodology (SE, VDD and VSSD) transforms the information outlined in Chapter 6 into the required format to solve the design problem.

7.1.1 The System Engineering Approach

The Systems Engineering approach transforms the information outlined in Chapter 6 into a list of requirements. Normally detailed discussions (brainstorming, focus groups, interviews, observation and questionnaires) between the systems engineer and the numerous stakeholders are performed to obtain this information. In this study, however, a generic specification of a 150 passenger aircraft was used to identify all of the requirements. Table 13 to Table 18 represent all of the notional requirements elicited in

this research for the SE approach. It should however be noted that some of these requirements (notably emissions and operating costs) have been modified to reflect the use of the CFM56-3 engine which was the latest publically obtainable engine data available for use within this research.

Table 13 – Basic Customer Needs Defined By System Engineering

ID	Description	Requirement
01	Number of Passengers	≥ 150
02	Design Range	≥ 3000 nmi
03	Cruise Speed	≥ 0.76 Mach
04	RDT&E Costs	≤ 11,500 M\$
05	Manufacturing Costs	≤ 115 M\$
06	Aircraft Price	≤ 130 M\$
07	Disposal Costs	≤ 14 M\$
08	Economy Class - Seat Pitch	≥ 30 in
09	Economy Class - Seat Width	≥ 18 in

Table 14 – Additional Aircraft Requirements Defined By System Engineering

ID	Description	Requirement
01	LD3-45 Cargo Boxes	≥ 4
02	All Fuel Stored in wings for maximum design range	Yes
03	Fuselage Length	≤ 140 ft
04	Two CFM56-3 engines are used and located under wing	Yes

Table 15 – Airport Regulations Defined By System Engineering

ID	Description	Requirement
01	Take-off Field Length	≤ 7,000 ft
02	Landing Field Length	≤ 7,000 ft
03	Landing Speed	≤ 141 knots
04	Wing Span	≤ 118 ft
05	Flyover Noise	≤ 120 dB
06	Side-line Noise	≤ 120 dB

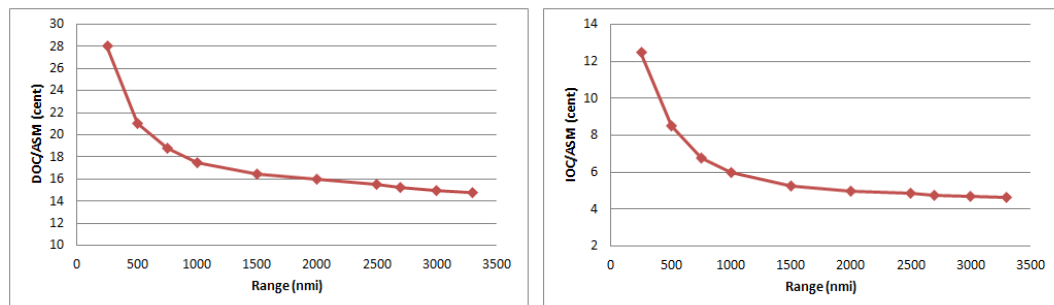
Table 16 – Acceptable Cabin Layout Defined By System Engineering

ID	Description	Requirement
01	First Class - Seat Width	≥ 25 in
02	First Class - Seat Pitch	= 40 in
03	First Class - Distance From Top Of Seat To Overhead Bin	≥ 15 in
04	First Class - Seating Configuration	2x2 Layout
05	Number Of First Class Passenger Seats	12
06	Economy Class - Distance From Top Of Seat To Overhead Bin	≥ 12 in
07	Economy Class - Seating Configuration	3x3 Layout
08	Aisle Height	≥ 6.5 ft
09	Aisle Width	≥ 20 in
10	Min. Carry On Bag To Be Stored In Overhead Bins (Every Passenger)	22x18x10 in

Table 17 – Acceptable Airline Operating Costs Defined By System Engineering

ID	Description	Requirement
01	DOC/ASM - Stage Length 250 nmi	≤ 28 ¢
02	DOC/ASM - Stage Length 500 nmi	≤ 21 ¢
03	DOC/ASM - Stage Length 750 nmi	≤ 18.75 ¢
04	DOC/ASM - Stage Length 1000 nmi	≤ 17.5 ¢
05	DOC/ASM - Stage Length 1500 nmi	≤ 16.5 ¢
06	DOC/ASM - Stage Length 2000 nmi	≤ 16 ¢
07	DOC/ASM - Stage Length 2500 nmi	≤ 15.5 ¢
08	DOC/ASM - Stage Length 2700 nmi	≤ 15.25 ¢
09	DOC/ASM - Stage Length 3000 nmi	≤ 15 ¢
10	DOC/ASM - Stage Length 3300 nmi	≤ 14.75 ¢
11	IOC/ASM - Stage Length 250 nmi	≤ 12.5 ¢
12	IOC/ASM - Stage Length 500 nmi	≤ 8.5 ¢
13	IOC/ASM - Stage Length 750 nmi	≤ 6.75 ¢
14	IOC/ASM - Stage Length 1000 nmi	≤ 6 ¢
15	IOC/ASM - Stage Length 1500 nmi	≤ 5.25 ¢
16	IOC/ASM - Stage Length 2000 nmi	≤ 5 ¢
17	IOC/ASM - Stage Length 2500 nmi	≤ 4.85 ¢
18	IOC/ASM - Stage Length 2700 nmi	≤ 4.78 ¢
19	IOC/ASM - Stage Length 3000 nmi	≤ 4.7 ¢
20	IOC/ASM - Stage Length 3300 nmi	≤ 4.65 ¢

Table 17 is represented graphically in Figure 36.



a) Acceptable DOC/ASM vs Stage Length

b) Acceptable IOC/ASM vs Stage Length

Figure 36 – Acceptable Airline Operating Costs Defined By System Engineering

Table 18 – Acceptable Airline Operating Emissions Defined By System Engineering

ID	Description	Requirement
01	CO ₂ /ASM - Stage Length 250 nmi	≤ 5.25 oz
02	CO ₂ /ASM - Stage Length 500 nmi	≤ 4.25 oz
03	CO ₂ /ASM - Stage Length 750 nmi	≤ 3.75 oz
04	CO ₂ /ASM - Stage Length 1000 nmi	≤ 3.5 oz
05	CO ₂ /ASM - Stage Length 1500 nmi	≤ 3.3 oz
06	CO ₂ /ASM - Stage Length 2000 nmi	≤ 3.15 oz
07	CO ₂ /ASM - Stage Length 2500 nmi	≤ 3.1 oz
08	CO ₂ /ASM - Stage Length 2700 nmi	≤ 3.06 oz
09	CO ₂ /ASM - Stage Length 3000 nmi	≤ 3.04 oz
10	CO ₂ /ASM - Stage Length 3300 nmi	≤ 3 oz
11	NO _x /ASM - Stage Length 250 nmi	≤ 18.5 gr
12	NO _x /ASM - Stage Length 500 nmi	≤ 11 gr
13	NO _x /ASM - Stage Length 750 nmi	≤ 8.75 gr
14	NO _x /ASM - Stage Length 1000 nmi	≤ 7.6 gr
15	NO _x /ASM - Stage Length 1500 nmi	≤ 6.55 gr
16	NO _x /ASM - Stage Length 2000 nmi	≤ 6.25 gr
17	NO _x /ASM - Stage Length 2500 nmi	≤ 6.15 gr
18	NO _x /ASM - Stage Length 2700 nmi	≤ 6.1 gr
19	NO _x /ASM - Stage Length 3000 nmi	≤ 6.075 gr
20	NO _x /ASM - Stage Length 3300 nmi	≤ 6.05 gr

Table 18 is represented graphically in Figure 37.

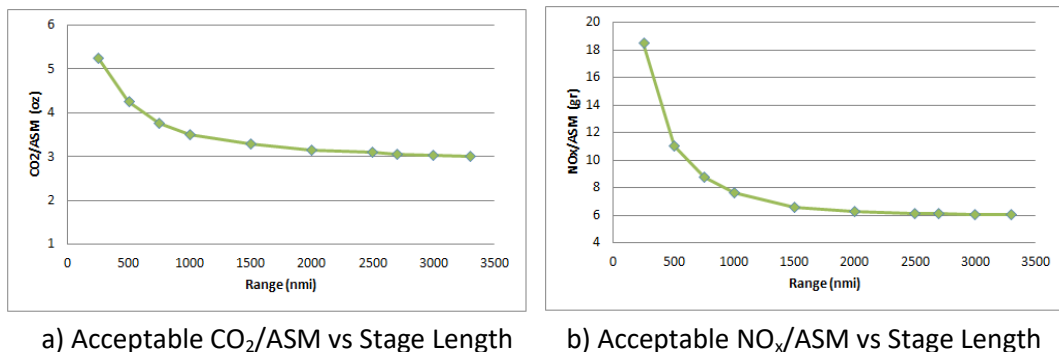


Figure 37 – Acceptable Airline Operating Emissions Defined By System Engineering

7.1.2 The Value Drive Design Approach

The Value Driven Design approach transforms the information outlined in Chapter 6 into a value model. To date the Value Driven Design approach has defined value as purely economic with surplus value being the choice of many authors and is the choice within this study. While this equation may be seen as a simplified economic function because it ignores competition effects, it does fit the basic principles of the Value Driven Design technique by being a system level objective function which has the ability to incorporate the value preferences of multiple stakeholders as well as important business factors. It is for these reasons that a surplus value objective function was chosen to be the evaluation criterion for the Value Driven Design study within this research.

To create the surplus value objective function previous authors have followed the steps outlined in chapter 1. This research however decided to use the surplus value equation proposed by Mullan [70] as it is the most recent surplus value equation proposed within the aircraft industry community. Mullan [70] equation has been repeated below for convenience.

$$V_s = r_p N_{a/c} \left[r_c F_y (R_{P\&C} - C_{OP} - C_{D\&C} - C_E) - C_M - C_{Disp} \right] - C_D \quad (2)$$

Where V_s is surplus value, r_p the discount multiplier based on a single year's revenue and costs for the manufacture, $N_{a/c}$ the total number of aircraft to be produced, r_c the discount multiplier based on a single year's revenue and costs for the customer, F_y the aircraft's annual utilisation, $R_{P\&C}$ the total airline revenue (for all flights and for both passengers and cargo), C_{OP} the aircraft's total operating cost (both direct and indirect), $C_{D\&C}$ the costs associated with flight delay and cancellation, C_E the externality costs (which is a representation of societal good, currently the costs associated with aircraft noise and

emissions), C_M the aircraft's manufacturing costs, C_{Disp} the aircraft's disposal costs and C_D the aircrafts research and development costs.

Analysing the surplus value equation (Equation 2) it can be seen that the customer discount multiplier (r_c), the manufacture discount multiplier (r_p) and fleet size ($N_{a/c}$) are all multipliers within this equation. A small change in any one of these factors could therefore have a major effect on a concepts surplus value. Within this study these factors will remain constant with the values displayed in Table 19. The discount multipliers were calculated using the equations within Ref [64] with the input values listed in Table 20.

Table 19 – Surplus Value Constants

Name	SV Symbol	Value
Fleet Size	$N_{a/c}$	1500
Customer Discount Multiplier	r_c	9.329
Manufacture Discount Multiplier	r_p	7.376

Table 20 – Discount Multiplier Input Values

Name	SV Symbol	Equation Inputs	Input Value
Customer Discount Multiplier	r_c	Discount Rate (%)	90
		Program Duration (years)	25
Manufacture Discount Multiplier	r_p	Discount Rate (%)	90
		Program Duration (years)	20

The remaining variables within the surplus value equation are generated via the FLOPS ALCCA program and the economic assumptions listed within Table 11 and Table 12. Once the results of the FLOPS ALCCA analysis are complete, the aircraft model automatically gathers the required surplus value inputs from FLOPS ALCCA output file to calculate the surplus value of each concept.

7.1.3 The Value Seeking System Design Approach

The Value Seeking System Design approach transforms the information outlined in Chapter 6 into a list of requirements and desirements. Normally detailed discussions (brainstorming, focus groups, interviews, observation and questionnaires) between the systems engineer and the numerous stakeholders are performed to obtain this information. In this study however a generic specification of a 150 passenger aircraft was used to identify all of the requirements and the desirements for the VSSD approach.

A requirement is an aspect which the design must conform to whereas a desirement is a design aspect the designer should strive towards but not if it devalues the overall design. To demonstrate the difference between a requirement and a desirement consider the following two examples. The FAA has stated that for an aircraft to be classified as a design group III aircraft it must have a wing span between the following range; less than 118 feet but greater than or equal to 79 feet. This is clearly a requirement as failing to achieve this specification means it cannot be classed as design group III aircraft. Notice how the boundary between acceptable and unacceptable is clear and precise for a requirement. A desirement on the other hand does not have a definitive boundary; instead the transition is more gradual becoming more or less acceptable over a range of values. Seat pitch for instance is an important aspect to most passengers on an aircraft. The boundary between acceptable and unacceptable though is not as definitive as the FAA regulation, as passengers may be willing to accept a range of values depending upon the effects this has on the systems overall value. For instance a smaller seat pitch may still be acceptable if it reduces their ticket price or reduces the carbon footprint of their journey.

In this study it was assumed that all regulations would be applied as requirements within the VSSD approach. This includes aspects regarding airport regulations and aircraft emissions. It was also assumed that the acceptable airliner operating costs, cabin layout

and additional aircraft requirements identified within the System Engineering approach would also be requirements in the VSSD approach. Table 14 to Table 18 therefore also represent all the requirements applied within the VSSD approach.

All of the desirements identified within this study are listed in Table 21 with the accompanying desirability function illustrated in Figure 38. Table 21 indicates the upper and lower boundaries of each desirement while Figure 38 captures the preference of the stakeholders within this range. All desirements were identified through market analysis, research and discussions with fellow researchers. One of the conclusions of this undertaking was that people are normally willing to slightly exceed their cost limit if the system provides more value to them. Additionally it was agreed that a lower cost system was more desirable with the desirability descending as the costs increases. The decrease however was not linear but instead followed a curve. This conclusion is reflected in all cost curves with the shape and ranges identified in a similar manner for all desirements.

Table 21 – Desirements Defined By Value Seeking System Design

ID	Variable Name	Lower Boundary	Upper Boundary	Unit
01	Number of Passengers	132	168	-
02	Design Range	2700	3300	nmi
03	Cruise Speed	0.76	0.8	Mach
04	RDT&E Costs	0	12	B\$
05	Manufacturing Costs	0	120	M\$
06	Aircraft Price	0	140	M\$
07	Disposal Costs	0	15	M\$
08	Economy Class - Seat Pitch	28	32	in
09	Economy Class - Seat Width	18	22	In

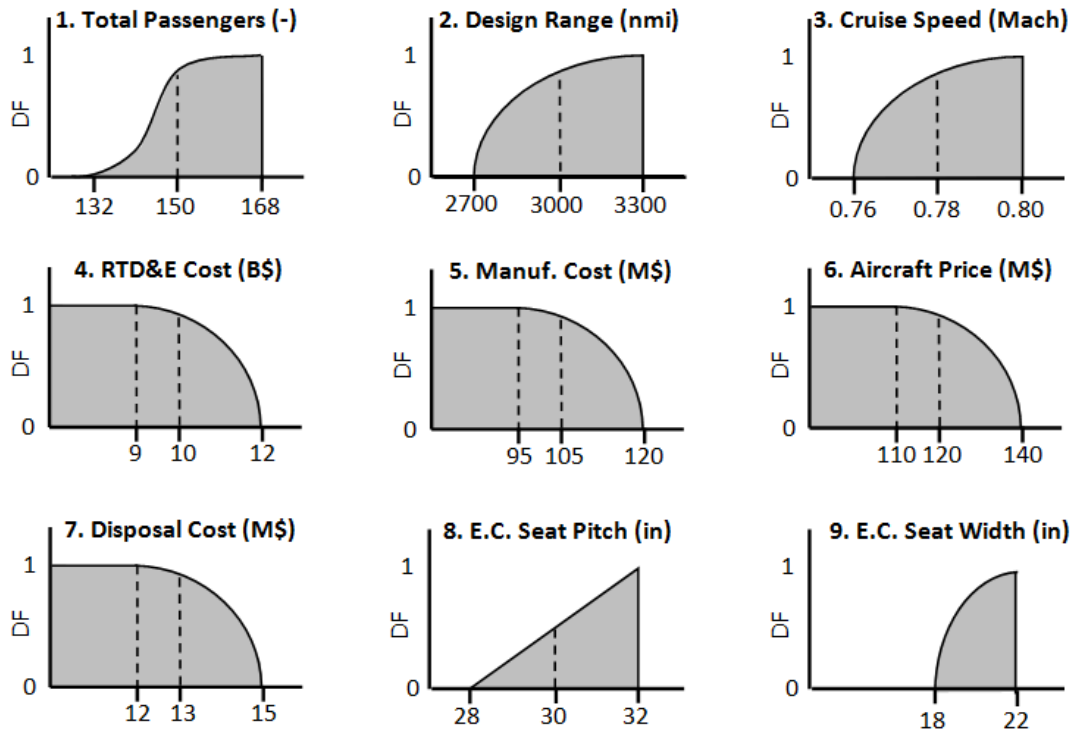


Figure 38 – Corresponding Desirability Function For Each Desirement

After generating the list of requirements and the list of desirements, the next step was to create the value function. This was achieved by following the steps outlined in Figure 20 (Section 4.2 of this thesis). To determine the value aspects important in this problem and hence the aspects to include within the value function, value statements were generated from the perspective of various stakeholders. Value statements are short sentences which can be written in natural language to capture the aspects which each stakeholder believes will add value to the design. In this study, value statements from each stakeholder were created independently (to avoid anchoring or bias) with additional value statements generated through a market analysis and discussions with fellow researchers. Three examples of the value statements generated through this process are listed below which highlight the value focus of this study.

“I value an aircraft which provides comfort allowing me and my family to travel safely to our destination” – Passenger

“I want an aircraft that is competitive on price” – Airline Operator

“We want affordable prices but not at the expense of the environment” – Society

After compiling and analysing all of the value statements, common stakeholder values were identified. These included but not limited to an aircraft that is economical, environmentally friendly and has a high mission capability. While these statements are easily understood, they are unsuitable to design towards, due to their subjective nature. To overcome this problem this study employed the House of Quality (HoQ) technique to transform these stakeholder values into system characteristics. The major advantage of using the HoQ technique was that it provided transparency and traceability of this transformation while automatically weighting each system characteristics for the value function. Figure 39 illustrates the HoQ created from the value statements within this study.

Key
 ⊙ Strong Relationship
 ○ Moderate Relationship
 △ Weak Relationship
 ↑ Objective Is To Maximise
 ↓ Objective Is To Minimise

System Characteristics		Performance			Economic			Social						
		Design Range	Passenger Capacity	No. of Flights Per Year	Profit Per Year	Aircraft Price	Disposal Costs	Seat Width	Seat Pitch	Distance To Overhead Bin	Noise	NOx	CO2	
Stakeholder Wants		(nmi)	(-)	(-)	(M\$)	(M\$)	(M\$)	(inch)	(inch)	(inch)	(dB)	(lb)	(lb)	
		↑	↑	↑	↑	↓	↓	↑	↑	↑	↓	↓	↓	
Performance	High Mission Capability	5	⊙	○							△	○	○	
	Maximise Seat Availability	2		⊙		○	△	⊙	⊙					
	High Aircraft Utilisation	4	○	○							△	○	○	
Economic	Affordable	3				⊙								
	Economical	5			○	○					△		○	
Social	High Passenger Comfort	3						⊙	⊙	○	△			
	Environmentally Friendly	4					△				○	○	⊙	
Relative Weighting			11.6	3.7	10.4	9.2	9.8	5.3	9.2	9.2	1.8	5.9	8.0	15.9

Figure 39 – House Of Quality Generated Through The VSSD approach

The completed HoQ was then used to build the value function within the VSSD approach. The system characteristics and their relative weighting became the design variables and their weighting factors within the value function. Each variable was then non-dimensionalised according to the design goal (represented by the arrow directly below the

system characteristic unit within the HoQ) to enable the value function to create a single value score. If the goal is to maximise (\uparrow) the system characteristic, the concepts system characteristic is divided by the baseline value. If the goal is to minimise (\downarrow) the system characteristic the baseline value is divided by the concepts system characteristic. The assumed baseline value for each system characteristic is listed in Table 22. The baselines are representative of a generic 150 passenger aircraft although they have been modified to reflect the use of the CFM56-3 engine.

Table 22 – VSSD Baseline Values For Value Function

System Characteristic	Baseline Value
Design Range (nmi)	3000
Passenger Capacity (-)	150
Number Of Flights Per Year (-)	950
Profit Per Year (M\$)	12
Aircraft Price (M\$)	125
Disposal Costs (M\$)	14
Seat Width (inch)	20
Seat Pitch (inch)	30
Distance To Overhead Bin (inch)	18
Noise (dB)	116
NOx (Ton)	100
CO2 (Ton)	23000

To complete the value function, the final step is to incorporate the desirability functions associated with the system characteristics. The desirability function is essentially a correction factor applied to the non-dimensionalised score, to include the desire of the stakeholder within the evaluation criteria. If no desirability function has been defined by

the system stakeholders for a particular system characteristic, the desirability function is assumed to have a constant value of one. Equation 23 is the value function created by the VSSD approach.

$$VSSD (OF)^* = f (\text{Performance, Economic, Social})$$

$$\begin{aligned}
 VSSD (OF)^* = & \left[11.6 \left(DF_{\text{Design Range}} \right) \frac{X_{\text{Design Range}}}{X_{\text{Design Range BL}}} + 3.7 \left(DF_{\text{Passenger Capacity}} \right) \frac{X_{\text{Passenger Capacity}}}{X_{\text{Passenger Capacity BL}}} + 10.4 \frac{X_{\text{Flights Per Year}}}{X_{\text{Flights Per Year BL}}} \right] + \\
 & \underbrace{\hspace{15em}}_{\text{Performance}} \\
 & \left[9.2 \frac{X_{\text{Profit Per Year}}}{X_{\text{Profit Per Year BL}}} + 9.8 \left(DF_{\text{Aircraft Price}} \right) \frac{X_{\text{Aircraft Price BL}}}{X_{\text{Aircraft Price}}} + 5.3 \left(DF_{\text{Disposal Costs}} \right) \frac{X_{\text{Disposal Costs BL}}}{X_{\text{Disposal Costs}}} \right] + \\
 & \underbrace{\hspace{15em}}_{\text{Economic}} \\
 & \left[9.2 \left(DF_{\text{Seat Width}} \right) \frac{X_{\text{Seat Width}}}{X_{\text{Seat Width BL}}} + 9.2 \left(DF_{\text{Seat Pitch}} \right) \frac{X_{\text{Seat Pitch}}}{X_{\text{Seat Pitch BL}}} + 1.8 \frac{X_{\text{Distance to Overhead Bin}}}{X_{\text{Distance to Overhead Bin BL}}} + 5.9 \frac{X_{\text{Noise BL}}}{X_{\text{Noise}}} + 8.0 \frac{X_{\text{NOx BL}}}{X_{\text{NOx}}} + 15.9 \frac{X_{\text{CO2 BL}}}{X_{\text{CO2}}} \right] \\
 & \underbrace{\hspace{15em}}_{\text{Social}}
 \end{aligned} \tag{23}$$

***Value Seeking System Design (Objective Function)**

Concepts that fail to pass all requirements and desirements however provide no value to the system stakeholders, as the design does not fulfil their needs. When a concept fails a requirement or desirement the model returns a zero value score to indicate their needs have not been met.

7.2 Prediction Profiler

To understand the design space and to assist in the decision making process a metamodel of the aircraft model was created. The metamodel was constructed using the statistical software package known as JMP which computed the response surface equation for each response through regression techniques. To generate the necessary data to create the response surface equations a design of experiments (DoE) was performed. The DoE was created within the JMP software which also determined the number of runs and the value each variable of interest should be set to. The DoE design chosen for this study was the

face centred central composite design (FCCCD) as it investigates every level end-point and centre point of the interested design space without requiring another levels bar (-1, 0, +1), reducing the required number of original model simulations to create the response surface.

The first step in creating the response surface equations was identifying the design variables, the design variable ranges and the responses metrics of interest. Once these had been determined they were entered into the JMP software to create the DoE table. To remove design variables which have no significant effect on the responses of interest, a screening test was performed. Design variables found to have no significant effect were removed from the DoE variables and become constant throughout the study. The geometry variables of the horizontal and vertical tails were design variables screened out. Reducing the number of design variables reduced the required number of experiments/simulations necessary to create the response surface equations. The simulations requested by the DoE were then entered into the simulation tab of the aircraft model to generate the results. The aircraft model was created to automatically generate the inputs files required for both the FLOPS and ALCCA programs. Once the input files had been generated the aircraft model automatically executed these simulations and collected the necessary outputs from the results files. The model then generated the surplus value and value defined by the VSSD technique based on this information and the assumed model inputs. Once the aircraft model was finished the responses of each simulation were then entered into the JMP software to complete the DoE table.

After populating the DoE table, the JMP software created the response surface equations through the analyses and fit model option. The equations were then analysed for goodness of fit to ensure they were capable of predicting within the specified variable range, to a high level of confidence. All response surface equations passed the statistical check ($R^2 >$

0.99), error check and validation check; indicating that all equations were suitable to predict the responses.

The final list of design variables and responses for the metamodel are listed in Table 23. Since the study includes 13 design variables, the DoE needed to create the response surface equations required 129 simulations.

Table 23 – Design Variables And Responses For Metamodel

Design Variable	Response
Passenger Number (-)	Wing Fuel Capacity (lb)
Design Range (nmi)	Wing Span (ft)
Cruise Mach Number (Mach)	Operating Weight (lb)
Max Cruise Altitude (ft)	TOGW (lb)
Fuselage Diameter (ft)	Take-Off Field Length (ft)
Composite FCOMP (%)	Landing Field Length (ft)
Wing Aspect Ratio (-)	Landing Speed (knots)
Wing Thickness to Chord Ratio (-)	Number Of Flights Per Year (-)
Economy Seat Pitch (in)	Profit Per Year (M\$)
Subsonic Drag Coefficient (-)	RDT&E Costs (M\$)
Fuel Flow Factor (-)	Total Manufacturing Costs (M\$)
Thrust To Weight Ratio (-)	Aircraft Life-Cycle Costs (M\$)
Wing Loading (lbf/ft ²)	Aircraft Price (M\$)
	Seat Width (in)
	Flyover Noise (dB)
	Aircraft NO _x Emitted Per Year (Ton)
	Aircraft CO ₂ Emitted Per Year (Ton)
	VDD Surplus Value (B\$)

One notable response missing from Table 23 is the VSSD value score. This response was not included within the prediction profiler because of pass/fail condition placed on the metric; if the concept failed to pass all of the requirements or be within the desirements range, the value score would become zero.

Figure 40 displays the prediction profiles from the metamodel which illustrates the sensitivity of each response to the design variables. The left hand side of the Figure 40 represents all of the responses with the design variables stated along the bottom. The range of each response and design variable is indicated by the accompanying scale. The slope of each curve indicates the measure of sensitivity between design variable and response. A steep slope indicates a significant influence between design variable and response. Shallow or almost horizontal curves do not mean that the design variables are unimportant; it means the variable has minor influence on the response, given the variable range analysed.

Since the prediction profiler could forecast the response change depending upon the design variable(s) altered in real time without the necessity of rerunning the aircraft model, the time and effort required to generate concepts was significantly reduced. Figure 40 for instance indicates that to minimise the CO₂ emissions of an aircraft, it should minimise the number of passengers, its design range and cruise speed, to name only but a few. Similar conclusions can be drawn from other prediction profilers.

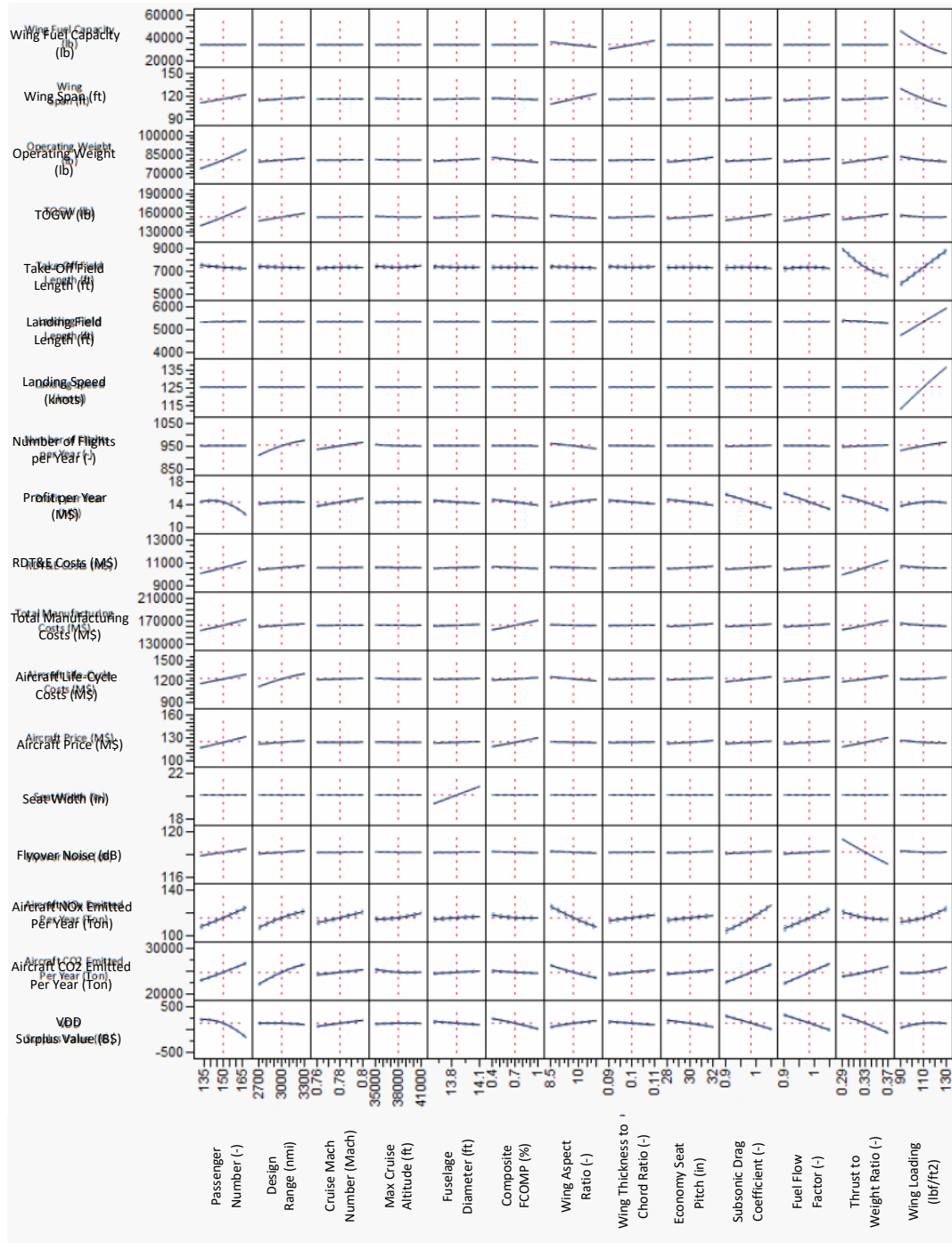


Figure 40 – Metamodel Prediction Profilers

7.3 Results

Table 24 displays 10 concepts that were generated within the study. They were created by following one of the three approaches. All of the concepts within Table 24 pass the list of regulations considered within the study and are therefore all viable solutions.

Table 24 – Results Of Study

		A	B	C	D	E	F	G	H	I	J	
Mission	Passenger Capacity (-)	132	138	144	150	150	156	162	162	168	168	
	Design Range (nmi)	2,700	3,000	3,300	2,700	3,000	2,700	3,000	3,300	2,700	3,300	
	Cruise Speed (Mach)	0.80	0.78	0.77	0.76	0.77	0.79	0.78	0.76	0.79	0.80	
	Cruise Altitude (ft)	37,000	37,000	41,000	35,000	39,000	39,000	35,000	37,000	37,000	37,000	
	T/W (-)	0.30	0.31	0.31	0.33	0.33	0.33	0.33	0.33	0.33	0.33	
	W/S (lbf/ft2)	90	95	95	100	100	100	105	105	105	105	
Sizing	Fuselage Length (ft)	119.41	124.95	127.32	129.70	133.34	132.07	134.45	134.45	138.88	136.82	
	Fuselage Diameter (ft)	13.60	13.75	13.70	14.10	13.60	13.70	14.10	13.65	13.85	13.60	
	Wing Span (ft)	113.79	115.25	117.69	115.00	117.48	116.86	117.88	117.80	117.56	117.74	
	Operating Empty Weight (lb)	69,523	75,821	79,281	80,418	82,584	82,208	86,473	86,557	88,746	87,259	
	Take-Off Gross Weight (lb)	126,664	140,983	149,530	148,604	154,204	151,744	162,103	165,589	164,912	167,313	
Material Info	Wing	Aluminium (%) : Composite (%)	55 : 45	65 : 35	70 : 30	60 : 40	70 : 30	65 : 35	65 : 35	70 : 30	70 : 30	60 : 40
	Body	Aluminium (%) : Composite (%)	73 : 27	79 : 21	82 : 18	76 : 24	82 : 18	79 : 21	79 : 21	82 : 18	82 : 18	76 : 24
Performance	Take-Off Field Length (ft)	6,911	6,931	6,874	6,644	6,615	6,627	6,926	6,912	6,915	6,905	
	Landing Field Length (ft)	4,766	4,919	4,923	5,046	5,050	5,049	5,205	5,214	5,213	5,213	
	Landing Approach Velocity (knots)	113.6	116.7	116.7	119.7	119.7	119.7	122.7	122.7	122.7	122.7	
	Number of Flights per Year (-)	900	940	959	898	942	916	958	965	922	997	
Economic	Profit Per Year (M\$)	16.20	16.05	16.21	13.22	14.57	14.38	13.81	13.70	12.20	14.54	
	Total RDT&E Costs (M\$)	9,344	9,943	10,230	10,462	10,650	10,589	10,940	11,011	11,065	11,103	
	Total Manufacturing Costs (M\$)	148,808	153,325	155,142	165,109	161,425	163,499	169,978	167,006	168,747	175,281	
	Life-Cycle Costs (M\$)	1002	1144	1215	1129	1216	1139	1268	1312	1197	1352	
	Final Aircraft Price (M\$)	113	117	118	126	123	125	129	127	129	133	
Social	Economy Class Seat Pitch (in)	28	30	30	30	32	30	30	30	31	30	
	Economy Class Seat Width (in)	19.375	19.875	19.625	20.875	19.375	19.625	20.875	19.500	20.125	19.375	
	Economy Class Head Space (in)	14.145	16.147	15.480	20.798	14.145	15.480	20.798	14.813	17.479	14.145	
	Flyover Noise (dB)	118.4	118.5	118.7	118.1	118.3	118.2	118.4	118.5	118.5	118.5	
	NO _x Per Year (Ton)	90.9	102.8	112.3	98.2	112.2	109.9	113.0	113.5	119.0	122.5	
	CO ₂ Per Year (Ton)	17,505	21,482	22,906	21,586	23,738	22,123	25,173	25,763	24,687	26,690	
Pass All Regulations	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	
System Engineering - Pass All Requirements	No	No	No	No	Yes	No	Yes	Yes	No	No	No	
Value Driven Design - Surplus Value (B\$)	477	405	395	29	181	163	31	32	-110	54		
Value Driven Design - Rank	1	2	3	9	4	5	8	7	10	6		
Value Seeking System Design – Value (-)	0.000	0.887	0.873	0.846	0.883	0.820	0.838	0.815	0.000	0.927		
Value Seeking System Design - Rank	10	2	4	5	3	7	6	8	9	1		

Of the 10 concepts generated 3 concepts were deemed acceptable via the SE approach (i.e. pass all requirements), 9 are deemed acceptable via the VDD approach (i.e. have a positive surplus value) and 8 are deemed acceptable via the VSSD approach (pass all requirements and desirements).

7.3.1 Selecting The Best Design

The value function employed in both the Value Driven Design and the Value Seeking System Design technique made the task of determining the best design intuitive and repeatable, as each concept was evaluated and ranked depending upon the value it offered stakeholders. The VDD approach selected "Concept A" since it had the highest surplus value while the VSSD approach selected "Concept J" as it passed all of the VSSD requirements, was within the ranges of the desirements and had the highest value score defined by the VSSD objective function. Although the results in Table 24 indicate similar conclusions for the VDD and VSSD approaches on the best design concept, the VDD approach was always willing to sacrifice performance and social aspects of the design, even those desirable to the stakeholders, for gains in surplus value. This occasionally caused the VDD technique to make financially myopic decisions where the gains in surplus value would be considered minor compared to the performance or social aspect decrease. The VSSD approach did not suffer this limitation as the VSSD value function considered all of three value aspects i.e. performance, economic and social within its evaluation criteria.

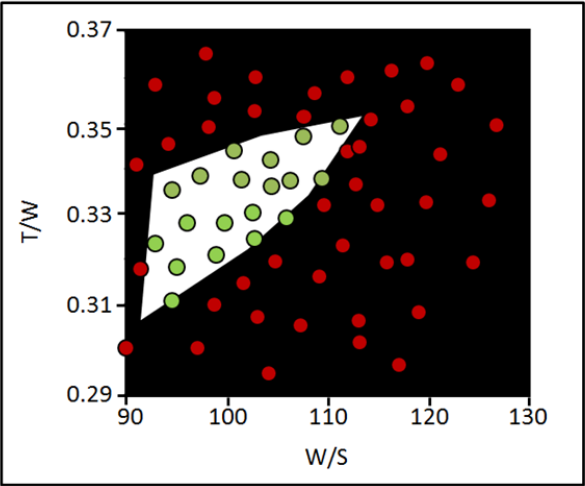
Selecting the final design using the System Engineering approach however was not intuitive or repeatable. While the SE approach was able to differentiate between designs that passed requirements and those that did not, it was unable to determine which design was best between the three concepts (i.e. "Concept E", "Concept G", "Concept H") that passed all SE requirements, as there was no dominate design. As the System Engineering technique provides no universally agreed method of determining the best concept when this occurs,

the preference was left to the designer to decide; removing the repeatability aspect of the process. While any aspect could have been chosen, it was assumed in this study that the concept which passed all requirements and had the lowest life-cycle cost (i.e. "Concept E") would be selected as the best design according to the SE technique.

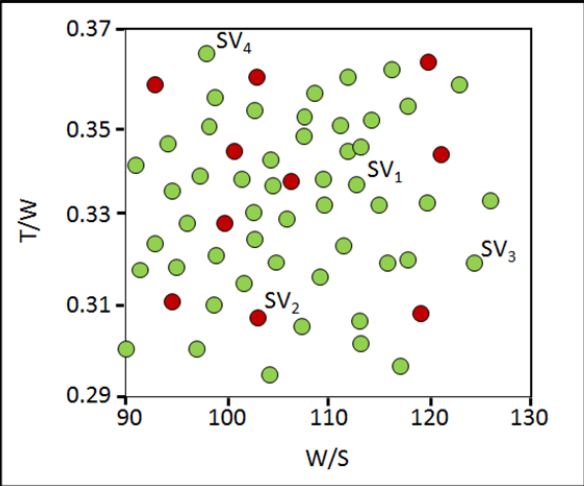
7.3.2 Solution Spaces

Figure 41 illustrates the solution space created by each technique analysed in this study. Figure 41a is the solution space created by the System Engineering technique, Figure 41b the solution space created by the Value Driven Design technique and Figure 41c the solution space created by the Value Seeking System Design technique. Randomly selected design concepts indicated as points in Figure 41 have also been incorporated to illustrate where acceptable and nonacceptable solutions may be found within each methodologies solution space.

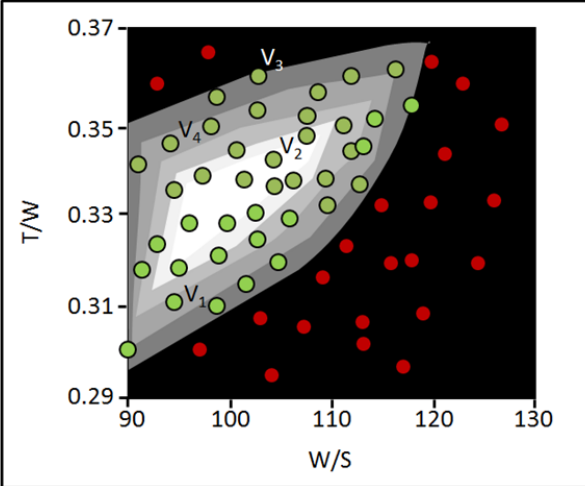
System Engineering



Value Driven Design



Value Seeking System Design



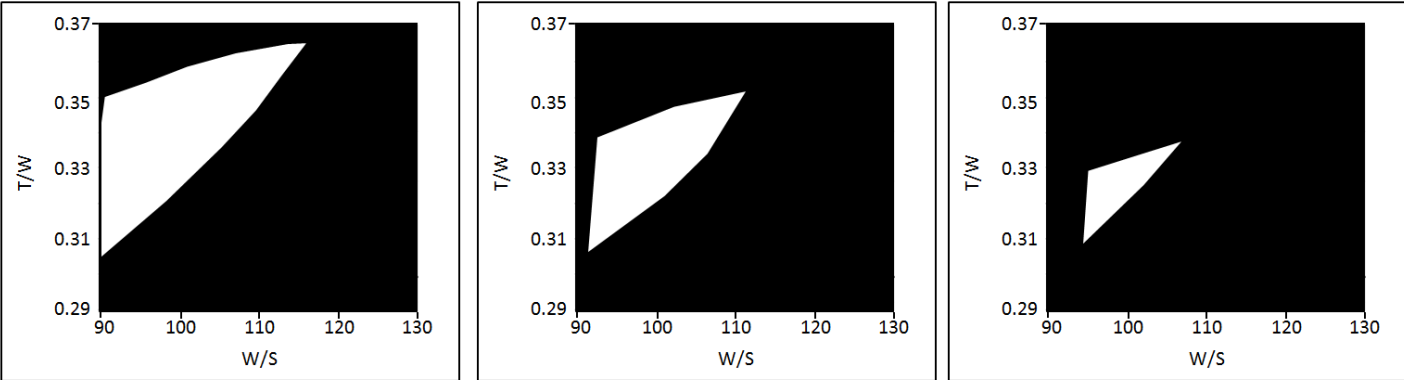
● Acceptable Design ● Unacceptable Design

Figure 41 – Solution Space Created By Each Technique

From Figure 41 it is clear that each approach creates a different solution space. The System Engineering approach for instance creates a rigid solution space defined by requirements. The requirements split the solution into either acceptable or nonacceptable regions, indicated by the white and black areas respectively within Figure 41a. The Value Driven Design technique on the other hand is not constrained by meeting requirements and creates only an acceptable solution space. This is highlighted by the fact there is no nonacceptable regions (i.e. black areas) within the VDD solution space. The Value Seeking System Design solution space however is neither fixed nor non-existent but instead non rigid; able to expand or contract due to the technique use of desirements. The use of desirements creates these grey regions indicated in Figure 41c. Unlike the System Engineering design space, the solution space is not definitively split between acceptable and nonacceptable, instead the solution space gradually transitions between these regions with the level of acceptability decreasing as the design point moves towards the black areas.

Figure 42 illustrates how the size and shape of the solution space alters when the 150 passenger aircraft design range is altered from 2700 nmi to 3000 nmi and finally 3300 nmi assuming only requirements are used to capture stakeholder needs. Similarly Figure 43 illustrates how the solution space alters when an aircraft with a design range of 3000 nmi has its passenger capacity increased from 132 passengers to 150 passengers to finally 168 passengers. This represents how the use of desirements creates this non rigid solution space with regions having a varying degree of acceptability.

As expected the solution space created by the VDD technique was the largest followed by the VSSD technique and finally the SE.

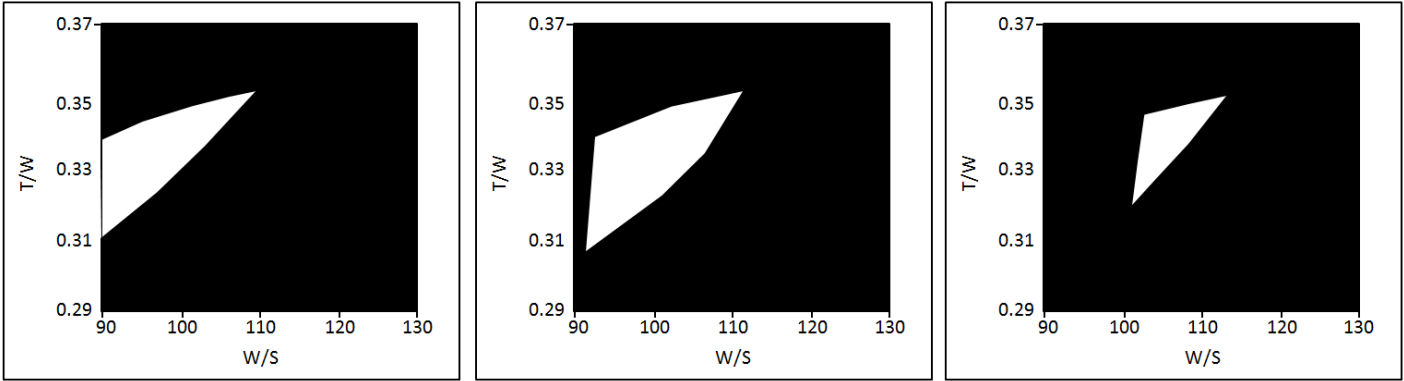


Design Range 2700 nmi

Design Range 3000 nmi

Design Range 3300 nmi

Figure 42 – The Effect Of Varying Design Range On The Solution Space



132 Passengers

150 Passengers

168 Passengers

Figure 43 – The Effect Of Varying Aircraft Passenger Capacity On The Solution Space

Of the 10 concepts stated within Table 24 only 3 are deemed acceptable while 7 are eliminated, including the top 3 economically viable solutions i.e. the 3 concepts with the highest surplus value. Upon investigation, most of these concepts were eliminated because they failed to pass the passenger capacity and design range requirements set by the airliner. All concepts presented in Table 24 though are viable (pass all regulations), indicating that requirements remove some of the viable solution space. "Concept A" for instance has many advantages over "Concept E"; most notably its costs are less and its annual emissions are lower but since it fails to meet the design range and passenger capacity requirements, it is deemed unacceptable and automatically rejected by the System Engineering process. The average passenger load factor and average stage length for a 150 passenger aircraft is 80% and 1000 nmi respectively [158]. "Concept A" can easily meet this need while also provide stakeholders with a higher surplus value design compared to "Concept E". The automatic rejection prevents a discussion between the designer and stakeholders taking place were a minor reduction in the requested design range or passenger capacity could provide a more economically feasible solution to the stakeholder needs. While it could be argued that these concepts are not what the stakeholders requested, the stakeholders were unaware the effects their requirements would have on the final system at the beginning of the design process. The necessity to find a solution which meets all requirements could therefore be preventing the designer from delivering a better solution to the stakeholder needs.

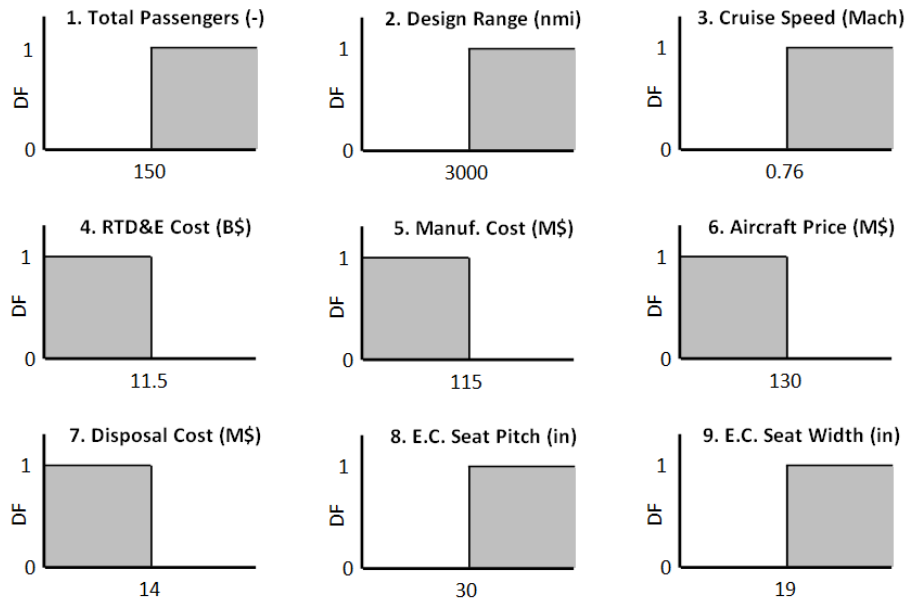
The solution space created by the Value Driven Design technique had two major problems. Firstly an open (unconstrained) solution space makes it virtually impossible to find the optimal solution given project resources and number of possible design configurations. Secondly unlike the other two techniques the solution space is not split into acceptable and nonacceptable regions making the process of determining if the design passed all regulations difficult. To overcome this issue, this study employed regulation requirements

within the Value Driven Design process. Although this did cause the solution space to reduce in size it did ensure only designs which passed all regulations could be considered as a possible solutions.

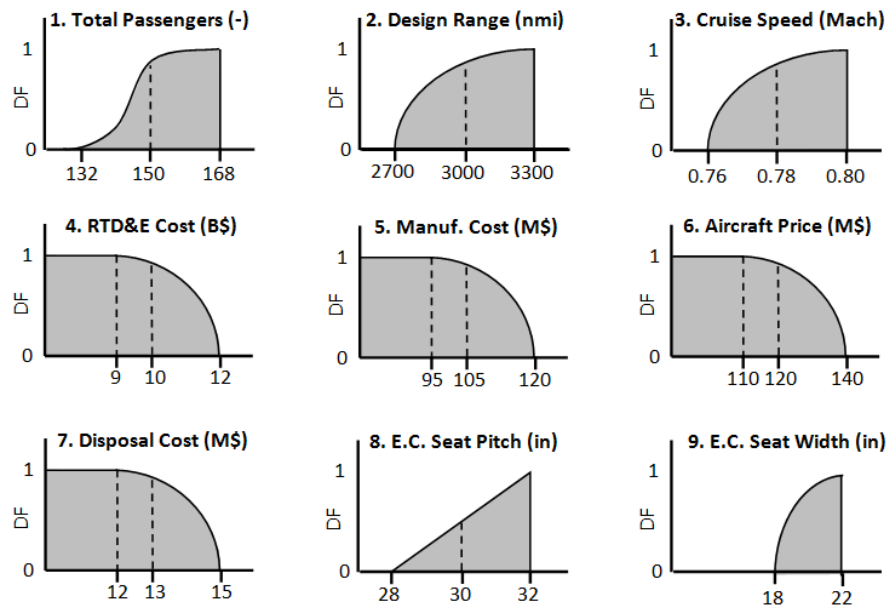
The solution space created by the VSSD technique offered the necessary balance between the SE and VDD approaches as it was neither rigid nor completely open as the shaded regions indicate. The techniques use of desirements allowed the design process to begin without unintentionally confining the design team to a predefined space. This give the designer the freedom to search for the most valuable design while also providing clear design goals; a characteristic missing from the VDD approach were the goal was simply maximise the designs surplus value.

7.3.3 Requirements vs Desirements

Requirements play a key role within the System Engineering technique. Some of the requirements identified in the System Engineering approach however were defined as desirements within the Value Seeking System Design technique. The effect this had on the desirability function is illustrated in Figure 44.



a) Stakeholder Needs Represented Graphically As Requirements



b) Stakeholder Needs Represented Graphically As Desirements

Figure 44 – Stakeholder Needs Represented As Requirements And Desirements

Analysing Figure 44, requirements have a sharp transition from desirable (i.e. acceptable) to non-desirable (i.e. non-acceptable) with the desirability function instantaneously switching between one and zero. The transition between these two states (i.e. acceptable and non-acceptable) for a desirement on the other hand is gradual.

One of the advantages of using desirements over requirements within the design process was the transfer of information between stakeholder and design team. To illustrate this consider Figure 45 which compares the total passenger need defined as a requirement and desirement.

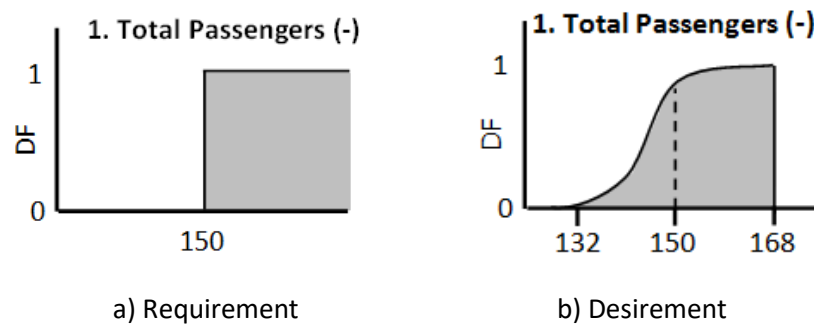


Figure 45 – Total Passenger Need

The requirement states that an aircraft with a passenger capacity of at least 150 passengers is required. The desirement however provides the design team with more information. In this instance the stakeholders would be willing to accept an aircraft which had a passenger capacity between the range of 132 and 168, if the outcome was more valuable. The desirement also informs the design team that while adding extra passenger capacity makes the concept more desirable, the desirability increase is nonlinear, with greater desirability improvement being achieved between 132 and 150 passengers compared to 150 and 168 passengers. Knowing this information can help the design team focus their attention on improving aspects which stakeholders would like, rather than attempting to improve an aspect that stakeholders are currently pleased with. Concept A for instance has a passenger capacity of 132 and a disposal cost of 12 million dollar. According to Figure 44 this disposal cost is highly desirable but there is no significant improvement gained from reducing it further. Increasing the passenger capacity though will have a great effect on the concepts desirability. Design efforts should therefore be focused on improving passenger capacity rather than reducing disposal costs. Additionally since the design process involves trade-

offs between various aspects, the desirability can highlight aspects that may be reduced without incurring a significant reduction in desirability. Reducing a concept's passenger capacity from 168 to 162 passengers for instance (i.e. removing one economy row of seats) only incurs a small decrease in desirability. The extra space this creates within the passenger compartment could be transferred to the seat pitch, greatly improving the desirability of this aspect. The desirability also informs the design team that an aircraft with a passenger capacity above 168 passengers is unwanted. None of this information is captured within a requirement but it is via a desirability, allowing designer to make better informed decisions on behalf the stakeholders.

7.4 Refuel Study

Until now, the aircraft model created within this research has been used to compare the SE, VDD and VSSD approaches. The aircraft model, however, is a comprehensive value model, able to perform value trade studies beyond the development of an aircraft. One such example of this is a refuel study.

The design range of an aircraft is an important aspect of its design, as it is the maximum distance a fully loaded aircraft can fly without refuelling. By increasing an aircraft's design range, it also increases its operational capability because it is able to perform longer non-stop routes. Operating long range aircraft on short routes however comes with a penalty of increased operating costs and emissions compared to aircraft with a lower design range. An airlines desire to have an aircraft with a large design range can therefore reduce the designs overall value, especially if it is mostly utilised on short stage lengths because it will incur these increased costs and emissions. This trade-off raises an interesting question, is it better to operate an aircraft which meets the full operational needs of the airliner or would it be better to split the long haul flights into two or more segments to allow an aircraft with

a smaller design range to perform the operation needs of the airline. To discover the answer to this question the following test case was created.

An airliner is hoping to operate the flights listed in Table 25.

Table 25 – Airliners Envisaged Flight Operation (Refuel Study)

Stage Length	250	500	750	1000	1500	2000	2500	2700	3000
Flights	60	108	140	194	162	126	86	72	52

The airliner has the choice between two designs concepts; “Design A” and “Design B”. Both designs are similar and meet all regulations. Both designs use the same percentage of composites, have the same passenger capacity and offer the same passenger level of comfort to passengers. The only noticeable difference between the two designs is their design range and wing geometry. The wing geometry has been altered to reduce drag but still carry all of the fuel required to complete their design range. An brief overview of the two designs is shown in Table 26 where “Design A” has a design range of 3000 nmi and “Design B” has a design range of 2000 nmi.

Table 26 – Design Comparison (Refuel Study)

	Design A	Design B
Range (nmi)	3000	2000
Cruise Speed (Mach)	0.78	0.78
Wing Span (ft)	113.68	107.20
Take-Off Field Length (ft)	6669	6763
Aircraft Price Mill(\$)	118	112

As “Design B” cannot fly above 2000 nmi, design ranges above this value have been split into two parts as shown in Table 27.

Table 27 – Stage Lengths For Refuelling (Refuel Study)

Original Stage Length (nmi)	New Stage Length (nmi)
2500	2000 + 750
2700	2000 + 1000
3000	2000 + 1500

While these design ranges could have been split further, the split was based upon the route which offered the most value to stakeholders; based on Equation 23. Since it is unrealistic to assume the refuelling airport is directly on the original long haul flight path additional miles have been added to account for the diversion to the refuelling airport. Additionally to remain competitive the ticket price for flights above 2000 nmi would remain fixed with the extra costs associated with refuelling absorbed by the airliner. While refuelling may allow additional passengers to be transported, as stopping at additional airport creates two new routes, this was not considered within this initial study.

After entering this information into the model and running the test cases, Figure 46 illustrates the results of this study.



Figure 46 – Results Comparison Between Design A And Design B (Refuel Study)

Figure 46 clearly shows that “Design B” is the best design for all stage lengths up to and including 2000 nmi as it has lower operating costs, emissions and the same revenue as “Design A”. Above 2000 nmi however the reverse is true with “Design A” out performing “Design B”.

The additional miles flown by “Design B” to perform the refuelling therefore significantly impacts the design and its value potential. In addition to fewer long haul flights being

performed (flights above 2000 nmi), which lowers revenue, the extra miles, take-off and landings associated with the refuelling also reduce profits because they are all additional costs incurred by the airliner to perform these long haul flights. Refuelling also causes extra emissions in both CO₂ and NO_x to be produced during these long haul flights, compared to “Design A”, further eroding the value of the “Design B”.

Figure 47 compares “Design A” to “Design B” over the annual operation on the number of flights, revenue, costs, profit, CO₂ emissions, NO_x emissions, surplus value (SV) and (VSSD) value.



Figure 47 – Annual Comparison Between Design A And Design B (Refuel Study)

Surprisingly there is a reduction in overall costs if the design team choice “Design B”. This however does not equate to higher profitability as the savings due lower costs are significantly lower than the lost in revenue. Overall the CO₂ emissions of “Design B” is lower than “Design A” meaning on this aspect it is better for the environment but comparing the NO_x emissions, “Design A” is superior. This increase in NO_x emissions is due to the additional

take-offs where aircraft engines produce high levels of NO_x. In all other aspects “Design A” dominates “Design B” informing the stakeholders that “Design A” should be their choice.

It was assumed at the start of the study that no additional passengers would be transported using “Design B” even though two new routes were created by stopping to refuel the aircraft. Since it is the economic viability of the “Design B” causing “Design A” to be selected, another study was conducted to determine how many additional passengers would be required to make “Design B” the superior choice. The load factor for all long haul flights will remain the same as the original study (0.84). This leaves a maximum load factor for the shorter nonstop flights to be 0.16 (i.e. $0.84 + 0.16 = 1.00$ which equates to an aircraft at full capacity) or 24 additional people ($150 \times 0.16 = 24$).

Since these additional passengers would be travelling on direct routes, they would be charged the normal price of that route. The long haul route with refuelling however only pays the cost for the long haul flight. Consider Figure 48 which demonstrated the pricing structure used within this study for the long haul flight and the two shorter nonstop routes.

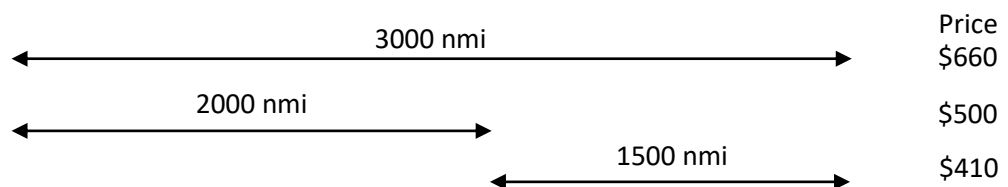


Figure 48 – Pricing Structure (Refuel Study)

After entering this information into the model and running the study, it was discovered that as the number of passengers increased the operating profit, surplus value and VSSD value all increased as expected for “Design B”. However even at full capacity (which equates to 24 additional passengers on every long haul flight) “Design A” is still be the best choice as “Design B” still isn’t economically superior to “Design A” nor does it have a higher VSSD value score.

Chapter 8: Conclusions

The aim of this research was to create an improved design methodology capable of designing complex systems. To achieve this ambition the current state of the art methodologies i.e. System Engineering (SE) and Value Driven Design (VDD) were initially reviewed, to discover why a new design processes was required. The review highlighted the advantages and limitations of the SE and VDD technique as well as the key elements which must be retained within the new design process. Following this review, Chapter 3 discussed the role which requirements and objective functions play within the design process; concluding that with a change in how stakeholder needs are captured and utilising a novel value function proposed by this research (Chapter 4) would significantly enhance the current design practice. The proposed value methodology, known as Value Seeking System Design, was then presented in Chapter 5 with the next two chapters focused on benchmarking the technique.

This chapter reviews the lessons which were learnt from this research; emphasising the main arguments and conclusions of this work. The key contributions to the current state of the knowledge are also outlined in this chapter along with future recommendations which are aimed at further developing this field.

8.1 Aim And Objectives Review

As stated in Chapter 2, the aim of this research was:

To develop a novel design methodology which combines the beneficial elements of both the System Engineering and Value Driven Design techniques into a new approach which addresses each other's weakness and ultimately provides designers with a tool which allows them to develop the most valuable system for their stakeholders.

To achieve this aim five research objectives were established. These objectives are reviewed in this section along with key findings resulting from their work.

Objective 1: Investigate the benefits and limitations associated with employing the traditional System Engineering and Value Driven Design techniques to develop complex systems.

In order to improve the current state of the art techniques it was first important to understand the benefits and limitations of the current approaches. Knowing this information the next step was to establish where these benefits and limitations stem from so they could be retained or eliminated within the Value Seeking System Design technique.

As the literature review and the 150 passenger aircraft study demonstrated, requirements play a vital role within System Engineering technique. While they transform the need of stakeholders into clear design targets, defining all stakeholder needs as requirements creates a rigid solution space which may unintentionally eliminate solutions that are more economically viable, as shown by the passenger aircraft study. Additionally while requirements provided an intuitive exit criterion, requirements by themselves are incapable of determining the best design, if there is no dominant design that passes all requirements.

The Value Driven Design technique on the other hand did not suffer from these limitations but it too was not without its issues. An example of this is the creation of the correct value function. Although the overarching value function is a fundamental element of the approach, as it drives all design decisions, so far there has been little to virtually no documentation on how stakeholder needs are transformed into this mathematical function. Additionally while the approach has the ability to determine the best design i.e. the highest scoring design, knowing when the maximum value has been achieved is not intuitive nor is

it possible to know from the value score alone whether all stakeholder needs have been fulfilled or even which needs had been satisfied and which ones had not.

If the benefits of both of these approaches could be combined, it would address the limitations of the current state of art approaches and create an enhanced design methodology for creating complex systems. Requirements and an overarching value function are therefore two key elements which must be retained within the new design process and are two key elements within the Value Seeking System Design technique.

Objective 2: Investigate the role an objective function has within the design process and understand how they are currently developed and implemented.

As a system level objective function is seen as a vital element within the new design process, it was important to get an understanding of how these functions are developed. To achieve this, a review of existing design optimisation methods and objective functions currently employed within the design community was performed.

The review emphasised the need to formulate the objective function correctly as an incorrect function would enviably cause designers to make wrong choices. An investigation into how objective functions have been developed and employed within SE, MDO and VDD communities was also performed. The purpose of this review was to understand the differences between these approaches and provide reasoning behind why there has been a shift from SE to MDO to now VDD within the aviation community. Like MDO, VDD seeks to further improve the optimisation process for designing complex systems. To achieve this, the VDD technique utilises a value function rather than using a traditional requirement based evaluation. In the aviation industry for example traditional requirement based functions predominately focused on one aspect and one part of the system life cycle. Value functions though have the ability to combine the needs and views of multiple stakeholders

throughout the complete system life cycle within one function; providing designers with a more balanced and accurate evaluation tool, allowing them to make better decisions. For this reason value functions are seen as superior functions compared to their predecessors and a key element within the Value Seeking System Design process.

To date, surplus value has been value function of choice for many studies utilising the Value Driven Design technique. While these studies have demonstrated that this metric can consider the views of multiple stakeholders (passengers, manufactures, operators and society) over the complete life cycle of the system, a key finding of this research highlights that this metric does have one major limitation; the current surplus value equation does not adequately capture or allow balanced value trade-offs to occur. At present the surplus value function only considers economic value and not the complete system value. While the founders of the surplus value equation encourage the inclusion of non-economic terms within the surplus value equation; this is a difficult task as these terms must first be monetised to ensure that a unique value score is retained. To overcome this difficulty, this research proposed an alternative value function, one which avoided the necessity to monetise metrics. The proposed value function instead non-dimensionalises each aspect using a baseline value. These non-dimensionalises metrics are then weighted and coupled with desirability factors to more accurately evaluate the system value to stakeholders. Two examples (family car and 150 passenger aircraft) of how to create a these value functions was provided within this thesis but they can be applied to any complex system.

Objective 3: Investigate and develop an understanding of the term value within the context of system design.

The review of objective functions stressed the importance of formulating them correctly, as failing to do so would unintentionally cause designers to make poor design trade-offs. As a system level value function would be utilised within the Value Seeking System Design

process, it was important to understand what value means within the context of system design; as a poorly created value function would never deliver the most valuable system. Value was the focus of Chapter 4 and examined how value it is defined and who ultimately determines what it is?

To date the term value within the context of design has been mostly ambiguous, with most definitions defining it as creating goodness and based on things stakeholders care about. It is therefore system stakeholders that define what is valuable about a system and have an important role in the creation of the system's value function. However unlike other metrics which designers have used in the past, like cost, value is an extrinsic property of a system; which varies depending upon the relationship the system has with other things including needs and stakeholders. While this unfortunately means there is no universal value function which can be applied to every design problem, this research proposed that a system's value consists of three fundamental aspects; performance, economic and social when fulfilling a need or needs of stakeholders. Performance values focus on a system's ability to accomplish certain functional needs, in other words what it can do and how well it does it. Economic value is concerned with financial aspect of the design; the revenue potential and costs over the complete life time of the system. Social values consider how a systems operation effects, interacts and/or is perceived by society. If an accurate value evaluation is to occur, these three aspects must be incorporated within the value function. The current surplus value equation is therefore too limiting as it only considers the economic value of a system and not its true value, unintentionally causing poor value trades to be made. This was demonstrated in the aircraft study where the VDD approach was always willing to sacrifice performance and social values for a gain (regardless of magnitude) in economic value.

Objective 4: Develop an innovative design methodology which retains the benefits associated with the current state of the techniques (SE & VDD) without suffering from their limitations.

Utilising the knowledge obtained from completing objectives one, two and three a novel design methodology known as Value Seeking System Design was created. The aim of the new design methodology was to retain the benefits associated with the SE and VDD techniques without suffering from their limitations. A detailed description of the steps involved within this VSSD approach is provided in Chapter 5. These steps have been written in generic form to allow the technique to be applied to the development of any complex system.

Although the new methodology has many similarities with the current state of the art approaches, the VSSD technique does have a couple of key differences. Unlike the SE approach which captures stakeholder needs through a list of requirements and the VDD technique of capturing stakeholder needs through an overarching value function, the VSSD technique uses both requirements and desirables to capture stakeholder needs. In this research desirables are design aspects which designers should be constantly striving towards but not if it devalues the overall system. Desirables are therefore not requirements, as these are design aspects which the design must conform to. Using VSSD, a novel approach to capturing stakeholder needs, the benefits associated with the current state of the art approaches are retained; as it provides designers with clear design targets but it avoids restricting them to a rigid solution space. The second difference is the evaluation criterion. While requirements provide SE with an intuitive exit criterion, they alone are incapable of determining the best design, if multiple designs pass all requirements and no design is dominant. The VDD use of a system level value function however does not suffer from these limitations. Instead the process can easily evaluate and rank designs based on the value it provides stakeholders while also avoiding designer bias;

improving the techniques transparency, traceability and repeatability. The system level function also prevents the design process falling victim to dead loss trades; design trades deemed to be good at local level but negative at system level. It was for these reasons that a system level value function would be employed within the VSSD technique. Although value functions are a superior evaluation tool, they do have one major drawback when compared to using requirements. It is impossible to tell from their score alone whether the design under evaluation is acceptable to the stakeholders or not, or what alternations are required to be made to make the design acceptable. To overcome this limitation, the VSSD approach will also utilise requirements and desirements within its evaluation criterion. The VSSD techniques use of requirements, desirements and a system level value function creates a superior evaluation criterion compared to the current state of the art techniques. It is through combining these three elements that the benefits associated with SE and VDD approach are retained while simultaneously addressing their limitations.

Objective 5: Benchmark the proposed technique against the current System Engineering and Value Driven Design technique.

To benchmark the VSSD approach against the current state of the art methods, a simplified design problem was generated i.e. the development of a new commercial aircraft. Each approach (SE, VDD and VSSD) was then tasked with developing the best solution to this problem. The process and results of the three approaches was then compared with one another to highlight the differences between the techniques.

To assist in accomplishing this task, a comprehensive and extensive value model of the design problem was created. The model linked a state of the art physics-based aircraft synthesis code with an enhanced life cycle assessment algorithm. The combined model was then further enhanced to incorporate existing value models as well as novel value models proposed in the current research. While value models have been used in the past, the value

considered within these models has predominately been based on performance and economic aspects, often overlooking the social value aspects of a design or only considering them as an afterthought once the performance and economic goals have been met. The value model created and used within the research however included the social value aspects within the value trade studies allowing a more balanced and accurate value trade off analysis to occur throughout the design process.

As expected, requirements played a key role within the System Engineering technique. While they transformed the need of stakeholders into clear design targets and provided an intuitive evaluation criteria, defining all stakeholder needs as requirements created a rigid solution space which unintentionally eliminated solutions that were more economically viable than the selected SE design. The study also confirmed that the current surplus value equation does not adequately capture or allow balanced value trade-offs to occur within the VDD approach, as the technique was always willing to sacrifice performance and social values for a gain in economic value. Furthermore it was impossible to determine from the value score only whether or not the design concept passed the entire list of stakeholder needs or even which needs had been satisfied and which ones had not. The Value Seeking System Design technique however did not suffer from these limitations. The value function created within the VSSD approach allowed a more balanced and accurate value trade off analysis to occur as it considered the performance, economic and social aspects of a design, avoiding the economic myopia of the surplus value equation. The VSSD use of requirements and desirements also ensured that the space remained open while also providing designers with clear design targets.

The results of the aircraft study verified that all three approaches (SE, VDD and VSSD) were capable of designing complex systems. The selected design, however, was dependant on the design methodology chosen, as all three methods selected a different design concept as

the “best” solution to the design problem. The design chosen by the SE approach remains debatable as there were multiple designs which passed all of the requirements but no dominate design. Nevertheless since stakeholders prefer aircraft with low life cycle cost, the design that passed all requirements and had the lowest life cycle cost was the chosen design via the SE technique. The Value Driven Design approach on the other hand was more intuitive, transparent and repeatable with the selected design concept being the one with the highest surplus value score. Similarly the Value Seeking System Design approach selected the design concept which passed the VSSD list of requirements, was within the range of the desirements and had the highest VSSD value score.

Overall the results of the VDD and VSSD techniques returned somewhat similar conclusions. This was not a surprising outcome as they are both value approaches. Upon investigation the differences between the techniques was due to the VSSD approach incorporating the social aspects within the value model. Thus, it is concluded that the VSSD approach captures the advantages of using a value-based design paradigm, such as VDD, but is a superior method due to its ability to more accurately capture a systems true value i.e. performance, economic and social value within its value model. The VSSD method is therefore seen as an improvement over the VDD and SE approach, and is preferred.

The results between the SE and value approaches (i.e. VDD and VSSD) however were significant. The SE approach focused on finding a solution which passed all requirements whereas the value approaches sought the highest value design. The value approaches were also able to determine which design was better or best, ensuring the best design option was chosen while also providing greater design traceability, especially within design decisions.

The simplified refuel study demonstrated the capability and benefits of using a comprehensive and extensive value model compared to traditional performance and/or

economic models. The key benefit of this type of value model was its ability to perform value trade studies beyond the development of the aircraft as it also allowed the decision maker to consider how the design would be utilised before selecting the final design.

A comparison between the System Engineering, Value Driven Design and Value Seeking System Design approaches is shown in Table 28 highlighting the similarities and differences between the approaches. As Table 28 demonstrates the VSSD approach combines the benefits of both SE and VDD to create an improved design process that is capable of developing complex systems.

Table 28 - Comparison Between SE, VDD And VSSD Approaches

ID	Description	SE	VDD	VSSD
01	An intuitive exit criterion	✓	✗	✓
02	Provides designers with design targets	✓	✗	✓
03	Value seeking philosophy	✗	✓	✓
04	Uniformed optimisation	✗	✓	✓
05	Can evaluate the value of a design option	✗	✓	✓
06	Non rigid solution space	✗	✓	✓

8.2 Novel Contributions To The State Of Art

The following list highlights the major contributions of this research.

A hybrid design methodology known as Value Seeking System Design (VSSD) has been created which uniquely utilises both requirements and value. Currently systems are designed to either meet requirements or maximise value. This research provides the first study to be conducted using the VSSD approach i.e. the development of a commercial aircraft.

The optimisation process is not constrained within a fixed or undefined solution space. Instead the solution space is non-rigid due to the unique way stakeholder needs are

captured allowing designers to seek, evaluate and select the most valuable design while ensuring it still meets their needs.

To date the term 'value' has been mostly ambiguous, with most definitions defining it as 'creating goodness'. This research, however, sought to remove this ambiguity by clarifying what value meant in the context of system design. This research proposes that a system's value is a balance between the performance, economic and social aspects it offers its stakeholders while fulfilling a need(s). A method of how to capture these three aspects within a novel system level value function was also presented and demonstrated through two examples.

8.3 Future Work

The study performed within the research focused on the development of a commercial aircraft to demonstrate the feasibility of a new design methodology (VSSD). To achieve this the study used simplifying assumptions and only considered a limited number of design variables. It is therefore recommended that the VSSD technique be applied to a more complex problem to test the validity of the approach under a more realistic scenario. The approach should also be applied to the design of another complex system, in another industry to confirm the process is not restricted to the aviation industry.

The weighting aspect within the VSSD value function is one area which needs to be addressed in any future development. Currently this is determined through the House of Quality technique and while this approach delivers the desired effect, a better and more rigorous method of obtaining these weightings would enhance this method.

Another potentially interesting exercise not pursued in this research is the identification of common values held by a particular class and/or type of product. Although value is unique to every system and its stakeholders, knowing the valuable aspects of comparable products

can reduce the risk of important values unintentionally being omitted. Additionally if changes in value were tracked between product generations, designers may discover trends which the new system should exploit that may not be obvious by simply comparing the proposed system to its predecessors and/or its competitors.

8.4 Concluding Remarks

Although the system engineering process has assisted designers create many complex systems over the past sixty years, its rigid solution space and its inability to determine the best design still remain two of its greatest weaknesses. Similarly while the philosophy of Value Driven Design promotes the design of better value designs, the technique in its current form is difficult to implement and its use of a purely economic value function is misleading, causing designers to make economically myopic decisions.

Throughout this research the goal was to create an improved design methodology to develop complex systems. By building upon the foundations of the SE and VDD techniques, modifying how stakeholder needs are captured as well as employing an innovative system level value function this goal has been achieved.

The paper study conducted within this research demonstrates the potential of the VSSD technique, indicating that the approach should be investigated further. The next step requires the paper study to be applied to a real world scenario to assess the feasibility of the approach within a business environment. If this is successful it would add to growing momentum behind adapting value seeking methodologies to develop complex systems and be another step towards industry accepting these approaches.

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