The Application of Modified Adaptive Landscapes to Heuristic Modelling of Engine Concept Designs using Sparse Data

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Thesis Summary

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by Brian Price

The automotive internal combustion engine industry operates in a sector that relies on high production volumes for economies of scale, and dedicated production equipment for efficiency of operations and control of quality, yet is subject to the vagaries of a dynamic marketplace, with the need for constant change. These circumstances place pressure on engine designs to be optimised at launch to be competitive and meet market needs, yet be adaptable to uncertain requirements for change over their production life. Engine designers therefore need concept configuration evaluation tools that can assess architectures for resilience to geometric change over the production life of the product.

The problem of being resource efficient whilst having the capacity to adapt to changing environments is one that has been addressed in nature. Natural systems have evolved strategies of satisficing conflicting requirements whilst being resource efficient. The theory of adaptive landscapes helps us to visualise the adaptive capacity of potential morphological forms. A concept attribute analysis methodology based on satisficing and adaptive landscapes has been developed and tested for application to engine concept design. The Plateau, Flooded Adaptive Landscape technique (PFAL), has been evaluated against exemplar engine life histories and shows merit in aiding the decision-making process for concept designers working with sparse data. The process lets the designer visualise the attribute map, enabling them to make better trade-off decisions and share these with non-expert stakeholders to gain their input in final concept choices.

Keywords; Adaptive Landscapes, Engine Design, Automotive Engineering, Trade-offs, Product Design

"It is not the strongest of a species that survives, nor the most intelligent, but the one most adaptive to change"

Charles Darwin

Dedication

This work is dedicated to Margaret, Holly, Charles and George. If I have seen far, it is because I have stood on the rock of my family (apologies to Newton).

Acknowledgements

I would like to take this opportunity to thank a number of people who were instrumental in helping me through the research process:

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Former colleagues in the engines industry – You provided the impetus and the raw material for the forge, which made this work possible.

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Glossary of Terms & Abbreviations

2V/4V - Valves per cylinder in the engine design. Commonly four valves per cylinder (2 intake, 2 exhaust), but older or lower performance engines may have two valves per cylinder. The number of valves per cylinder (total) will generally be in the range 2-5.

5C - The core engine components: Cylinder block, cylinder head, crankshaft, camshaft and connecting rod.

AL - Adaptive Landscape. A biological metaphor that has subsequently been adopted by other disciplines.

Architecture - The physical disposition of the major engine components and systems.

Attribute - A defining physical or systemic characteristic of an engine's performance, such as power output, fuel economy, noise level, bore size, crank diameter, etc.

BDC - Bottom Dead Centre. The bottom of the stroke during the engine cycle, when the piston is at its lowest point.

BRICS - Brazil, Russia, India, China. A term more generally used to denote developing markets, regardless of national boundary.

CAE - Computer aided engineering. Used to describe any engineering analysis process using bespoke/specialist code.

Characteristic - An emblematic feature that defines the engine, system or component under consideration.

CFD - Computational fluid dynamics. Simulation of fluid flows using complex Navier-Stokes equations.

Configuration - A categorical arrangement of the major engine geometry including number and layout of cylinders, valvetrain arrangement, etc.

DFV - Double Four Valve. The designation for a family of engines developed by Cosworth as Formula One engines from 1967-1989. This is the most successful F1 engine of all time.

DNA - Deoxyribonucleic acid. The molecule that carried the genetic information use for growth, development, function and reproduction in living organisms.

Entity - A representative, distinct unit.

EoL - End of life. The point at which a product ceases to be manufactured.

Feature - A distinctive embodiment of an attribute.

FPE - Fire Pump Engine. The first design designation of the Coventry Climax range of light weight, high performance engines.

HDV - Heavy Duty Vehicle. Heavy trucks (over 4,500kg gross vehicle weight).

ICE - Internal Combustion Engine. Generic reference to all forms of combustion engine using an enclosed combustion process. In the context of this thesis it is applied to piston engine configurations. Alternative form 'IC engine'.

IMVP - International Motor Vehicle Program. MIT study in late 1990s into manufacturing practice benchmarks around the world. A number of reports were specifically written on automotive engine plants performance.

LCCA - Lifecycle Cost Analysis. An economic costing process to analyse whole life costs of purchase, operation and disposal.

LDV - Light Duty Vehicle. Cars and light trucks (under 4,500kg gross vehicle weight).

MAL - Modified adaptive landscapes. Adaptive landscape form modification through surface limitations (truncations, plateaus, flooding) to constrain feasible regions.

MIRA -Motor Industry Research Association.

NCSS - NCSS Statistical Software. A commercial software package used for advanced statistical analysis, including 3D surface generation.

NPD - New product development. The formalised process of stage-gates used to manage the design and delivery of a product from conception to market launch.

OEM - Original Equipment Manufacturer. The final brand aggregators of a product or service.

Parameter - A physical dimensional attribute value of an engine or component.

PFAL - Plateau, Flooded Adaptive Landscape. A specific form of adaptive landscape truncation with a fitness plateau in place of a peak value for fitness and a limiting minimal fitness value (flooded plane).

Plasticity - An ability to change.

Resilience - An ability to adapt to change.

Robustness - An ability to resist shock or the impacts of change.

SAE - Society of Automotive Engineers.

SMMT - Society of Motor Manufacturers and Traders.

SSM - Simplified surface model. A simple model of a 3D surface generated using Excel based tools and simple algorithms, for ease of analysis and representation.

TDC - Top Dead Centre. The top of the stroke during the engine cycle, when the piston is at the highest point in the cylinder.

TPS - Toyota Production System. A system for efficient process control, based on the principles of Lean engineering/manufacturing.

UPA - Units per annum. The number of individual units of production manufactured in one year.

Variant - An engine configuration of a related family, differentiated by key configurational difference e.g. number of cylinders, displacement, etc.

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1.0 Introduction

This chapter provides a brief overview of the research objectives, the application field of engine concept design and the thesis of using biological models of adaptive landscapes to evaluate engine concepts’ capacity for change over its production life to optimise resource investments and extend the production life of the engine.

1.1 Thesis Introduction

This research study was conducted to address a need in optimally managing the lifecycle of capital investments in engine production equipment. The author’s experience over a 30-year career in the design and development of engines had provided ample evidence of the constraints placed on the development of engines over time due to the limitations of investments made in existing production plant and equipment. The early stages of an engine’s concept design determines the major dimensions that will be used to specify the requirements for production lines that will be used over the production life of the product. Capital investments in plant and equipment for high volume automotive engines are typically between $500M-$1B. In seeking to minimise initial investments and make the manufacturing operation as efficient as possible, it is usual for production line equipment to be dedicated to the particular product being manufactured. This means that any subsequent changes in the product, especially if they involve a significant change in key dimensions, will have a large effect on the existing capital equipment. This is likely to mean further, expensive investment is required and possibly the early write-off of existing equipment.

The purpose of this research is to investigate whether a simple form of analysis can be conducted at the concept stage to highlight constraints that might be imposed by the adoption of particular geometry and to provide a tool for evaluating options for building change capacity into the initial design to avoid some or all of the cost of uncertain future developments of the engine over its production life.

In seeking to minimise resource consumption, yet retain some capacity for resilience to change, a biological analogy was followed. The engine design evolves over time in response to external pressures put on its operating environment, including emissions regulations, competitive pressures and new technology opportunities. This is akin to the process of evolution in nature, where biological entities must optimise their expenditure of precious resources to survive and reproduce, whilst ensuring that they are not so lean that they cannot survive occasional shocks to the environment that may stress their ability to evolve to accommodate a changed set of circumstances. Taking inspiration from biological models of adaptive landscapes, the research aims to apply this process to the selection of concept options for engine designs to make them robust to change over the production life of the product.

1.2 Aims of the Research and Objectives

The purpose of this research study is to evaluate the potential for biologically inspired adaptive models to help guide the decision-making process of engine designs at the concept stage. The premise for this approach is that in nature, biological entities must be both resource efficient in the short-term and resilient to change to survive in the long term. These are the same conditions that affect the viability of engine designs over their production life as they are required to be seen to be an efficient use of resources to gain initial investment approvals, but must change over their production life to match the needs of the market environment. By examining evolutionary approaches, we may be able to better establish the architecture of engines to trade-off competing requirements of efficiency (optimisation) and resilience (extra capacity).

The condition set that applies to engines as manufactured products are:

- Heavy capital investments for volume manufacture, with long production life.
- An optimised concept design for optimal use of resources for package size, weight and performance; produced on dedicated manufacturing equipment for efficient operations.
- A dynamic, competitive market, rapidly changing engine technologies and an increasingly restrictive legislative environment, resulting in pressure for regular, uncertain changes to key engine geometry.

The zone where these constraints occur is show diagrammatically in Figure 1. Products with a high capital investment, high levels of product optimisation and existing in a highly dynamic or uncertain environment have a need to balance optimised design with a capacity for change. If the production equipment has low capital intensity or can be written off over a relatively short period, then an effective strategy is simply to replace tooling and equipment rather than build geometric growth capacity into the product design. If the product design does not need to be optimised for cost, size and weight, it can afford to carry excess design capacity without the need for optimal analysis to limit this against product performance. If the product exists in a stable environment with little pressure for geometric change, then an initial design is likely to last the production life of the engine family. It is under the conditions illustrated in Figure 1 by the blue cube, that there is a need to optimise the concept geometry of a product whilst enabling defined future key architecture geometric change.

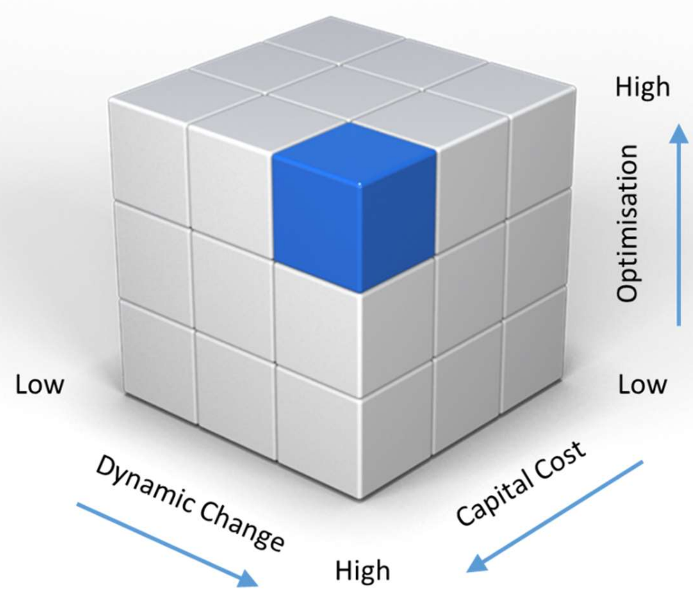

Figure 1 The Manufacturing Constraint Zone for Optimised Growth Capacity.

Decisions about engine product architecture are set at the concept design stage. This is a relatively short period in the overall product development process and is characterised by happening infrequently and under conditions of uncertainty. This places the designer under pressure to progress a design with limited information.

The aim of this research project is to develop a concept design decision support methodology to aid evaluation of engine architectures to optimise production lifetime return on investment of capital equipment.

To achieve this aim, several objectives were set:

- The methodology should be simple to apply and not require special tools or training.
- The approach should be intuitive to the designer and aid the design thinking process.
- The methodology should fit within the concept stage constraints of sparse data and limited resource.
- The output should be visual to aid evaluation by concept designers and communication to other stakeholders.

Heuristic adaptive landscapes were chosen as the principal model to be applied to concept design options.

The principal research question is "Can the principle of adaptive landscapes from biology be applied to product concept generation trade-offs in engine concept design".

1.3 Thesis Structure

The thesis structure progresses through the stages of the research activity to develop a method for assisting with evaluation of design geometries for new engine programs.

Chapter 1 Thesis Introduction - The introductory chapter provides some context setting information on the rationale for the research topic. An outline of the research problem is presented. Background on the engines industry and the constraints on new engines designs are provided. A brief description of the drivers for change in engines design in the automotive industry and the resulting engine production lifecycles is presented. This sets out the research problem.

The potential for using biological models to aid engine concept designer thinking is identified. The use of adaptive landscape visuals is offered as a potential mechanism for the consideration of creating a robust product morphology resilient to uncertain but probable change, over the production life of an engine family.

Chapter 2 Context and Literature Review - The second chapter provides more depth of background on the engine concept design process and product evolution over time under selective pressure, comparing this with evolutionary selective pressures and the effect that these have on physical morphology of plants and animals. How nature satisfices resource utilisation with competing requirements for survival capacity in dynamic natural environments is proposed as an analogous model for application in product design.

An overview of the engines industry is given, with a particular focus on automotive engines. The drivers for change in engine design over their production life is discussed. The production lifecycles of engine are calculated from secondary data, to be used as inputs into modelling future engines lifecycle planning. Historical evolution of engine products throughout their life are used to illustrate the number, scope and rate of engine major architecture geometry changes that are typically encountered. The impacts of these changes on the return on investments made and issues with sustainability are laid out. Various strategies for providing variety in engine design options whilst minimising investment costs are discussed, from modularity to flexible manufacturing and shared development.

The second half of Chapter 2 provides a review of natural evolutionary processes and a discussion of how the conflicting demands of resource utilisation and adaptive capacity are handled in nature. Alignments are drawn between the processes of change in engine design evolution and that of biological entities. It will be seen that the processes are very similar, albeit with very different environments. The concept of modelling capacity for change using adaptive landscapes is presented. The opportunity to apply this technique to product concept design to help establish resilient geometry configurations is proposed.

Chapter 3 Methodology - A mixed methods methodology for investigating the application of adaptive landscapes to human designed product is set out in Chapter 3. An understanding of the design process and its constraints for engine design is explored through the use of interviews and a survey of practising engine designers and other new product development professionals from the engines industry. The use of secondary and historical data on engine evolution over time is used to provide input information into subsequent modelling activity. In particular, the issue of sparse data as feasible design point benchmarks at the concept stage is discussed.

The concept of a *design space* is shown. Modelling methods for creating intermediate values between known points on the design space using von Neumann neighbourhood cellular automata methods are presented. The creation of 3D adaptive landscapes from this sparse data is proposed, including the selection process for attribute fitness values. Finally, a modified Norton-Bass model is proposed as a means of evaluating investment options for alternative concept design strategies. A validation process using retrospective engine production life data and verification of the proposed design method is proposed.

Chapter 4 Findings and Discussion - The modified adaptive landscape design process proposed in Chapter 3 is applied to an exemplar engine and tested against known engine evolution history - the Rover K series engine. The engine concept design process is described, and the results evaluated against a normative engine production lifecycle based on historical data. The modified Norton-Bass model is used to assess impacts on investment utilisation between dedicated production equipment which is traditionally used in engine manufacturing investments of this type and flexible manufacturing equipment that has benefited from key geometry growth capacity by the use of the adaptive landscape concept design process. Finally, perspectives on the validity of the process were sought from engineers active in engine design and development to assess whether the process had merit.

Chapter 5 Conclusions and Recommendations - The conclusions of the research study are presented in Chapter 5. These show that the PFAL process does have benefits in enabling designs to be more resilient to key architecture geometric change over their production life, compared to more traditional optimisation methods. The process allows designers and other product development stakeholders to make better informed decisions on product architecture. This allows for full production lifecycle planning, including more realistic planning of production end of life.

The benefits and limitations of the proposed method are presented. Further developments of the technique are discussed, with consideration given to process automation and dynamic modelling of environments. The PFAL process has potential to be applied to a wide range of product design and trade-off decision making situations beyond the scope of this thesis.

Appendices - Additional material has been included in the appendices for reference. This includes detail on data sources and potential types of errors as well as a detail description of the PFAL process, showing screen shots of the calculation sheets used. Alternative forms of adaptive landscape representation are also discussed, with opportunities for further development of the modelling process to improve ease of use for designers and other decision makers.

1.4 The Automotive Engines Industry

The piston engines industry covers all forms of internal combustion engine (IC engine). These include applications from small model aeroplane hobby engines of less than 2 cubic centimetres in size and >0.2cc displacement, to large marine ship engines of up to 7,370 cubic metres in size for the 2,300-ton engine and 1,820 litres displacement. These extremes of piston engine design use the same principles of operation and component design. A cross sectional drawing of these engines looks remarkably similar, with the features scaling parametrically with size. Internal combustion engines have been developed considerably over the last 150 years and have found applications in everything from handheld utility equipment like chainsaws and snow-blowers through industrial and generating equipment, to aircraft, ground transport and marine applications.

One of the largest uses of internal combustion engines is in the automotive sector. This accounts for global production of over 93 million engines produced each year, set to rise to over 110 million units annually by 2023 (OICA 2016, IHS 2015). The competitive environment in the automotive industry is becoming challenging, with diminishing sales in developed markets and new entrants in growth regions and new sectors such as electric vehicles. Technology developments in areas of hybridisation have accelerated in recent years, with several major manufacturers announcing strategies of hybrid and electric only product offerings by 2020. In almost all cases these still rely heavily on IC engines, albeit in downsized forms as part of a powertrain system with electric motors (Taylor 2017). The changes being driven by legislative and regulatory requirements for emissions and fuel efficiency are unprecedented in driving the reconfiguration of IC engine layout and design. Although the era of purely IC engine driven transport appears to be drawing to a close, not only is there still a future for IC engines, but it would appear we have entered a period of rapid innovation (Automotive UK 2013, van Besouw, Klostermann & Huijbers 2011).

The powertrain refers to the engine, gearbox and driveline for an engine system, including the incorporation of electric motors if hybridised or ancillary boosting equipment such as integrated energy systems (flywheels) or starter/generator systems (Anderson & Anderson 2010, Hoag 2008, Riley 2004). Reference to ‘engine’ is usually limited to the base piston engine part of any powertrain system. With hybridisation and more sophisticated integrated powertrain units, it is becoming increasingly difficult to separate engine design from related driveline systems (IEA 2011, Jeon 2010). For the purposes of this study, we will be concentrating on the base engine design and excluding associated gearbox and driveline components. However, as its configuration and arrangement is influenced and indeed driven by hybridisation, the design layout processes discussed here are the same and will apply to future generations of engine concept design and historical IC engines equally.

Due to the large investments required to produce the high volumes required for automotive industry applications, the need to optimise the configurations for package size and efficiency and the dynamic nature of the market and regulatory pressures on the industry, the automotive engine presents us with a perfect case study to investigate our research question.

1.4.1 Automotive Engines Production Lifecycle

This research project discusses the production manufacturing lifecycle of IC engines. Lifecycle discussions usually reference the build, usage and disposal of a single unit. That is not what is being referred to in this thesis, as it is principally concerned with the life of the manufacturing equipment used to produce the engine. The production lifecycle of an automotive engine is typically 10-12 years. In Chapter 2 an analysis of engine production life is conducted to establish patterns of duration and change for automotive engines. We will see that engine families consist of a number of engine variants, covering a range of displacements, power outputs, features and configurations. Some of these families have their various architectural configurations defined at the concept stage, but most engines typically require the introduction of unplanned variants at some point over their production life. It is the challenge of absorbing these unexpected variants into an existing production environment that is the core issue of this research study.

General patterns in automotive production lifecycles are derived to inform the scope of the problem for the wider engines industry. Specific example cases are investigated and used to replicate an exemplar engine family production life for evaluating alternative investments strategies enabled by building growth capacity for core engine geometry changes into the initial concept architecture.

For the purposes of this study an engine's ***architecture*** refers to the layout and arrangement of the engine components and systems. This is the geometric disposition of all major components. The engine ***configuration*** refers specifically to the number and arrangement of cylinders, a major determinant of engine package size and efficiency. The engine ***attributes*** are those aspects of an engine that characterise its performance. These may be physical geometry, but also include emissions, fuel economy, engine power, noise and other non-physical aspects. The design ***parameters*** of the engine concept design refer specifically to key dimensions of the engine such as bore and stroke, that have a large influence on not only package size and weight, but also other engine attributes such as power output and emissions.

The production lifecycle of an engine family may be prematurely ended when the engine attributes are no longer able to meet market requirements and the engine family architecture limits economically feasible change due to key engine geometry parameters being overly constrained by not having capacity for growth without significant knock-on effects to related componentry and their associated production equipment.

1.4.2 Drivers for Change

The need for a new engine configuration may come from market needs, regulatory or legislative demands, growth opportunities in new regions or sectors, or from a host of other imperatives. New technologies materials or manufacturing processes may present an opportunity for improvements in an existing design, but it is usually the realisation that an existing engine can no longer meet market needs or satisfy regulatory compliance that prompts concept design of a new engine.

The costs associated with designing and developing new engines are significant, with estimates of >$500M for a new engine design, including investment in manufacturing plant and equipment (Rankis, Simpkin & McGrath 1997). The rate of change is accelerating, as technologies for engines advance and environmental legislation plays a greater role in driving changes in acceptable engines configurations. Some legislation has banned certain engine configurations, such as two-stroke engines, regardless of how 'clean' those engines can be made to operate. Similar bans in urban areas are now being suggested for diesel engines and other particular forms of IC engine, as legislative bodies seek to achieve environmental targets. This means that engine designs that were considered state of the art only a few years ago are now subject to significant change pressures.

The engine designer is faced with the challenge of designing an engine architecture that is not only optimised to achieve known targets today, but will remain viable over its entire planned production life in the face of certain but undefined change.

1.5 Research Problem

The research problem is therefore how can an engine designer ensure that they have developed an engine architecture that will be resilient to uncertainty in a dynamic market, but is sufficiently optimised that it is competitive at the point of launch and is not carrying an excess burden of cost, weight or package size, to allow for growth potential. A methodology is required to enable engine concept designers and other stakeholders in the design of a new engine, to be able to assess the impacts of possible changes to key engine geometry over the production life of the design.

By having a clear understanding of the adaptability of the engine design to geometric changes and the limits to that growth potential, product developers can make informed decisions about investments in engine production equipment.

1.5.2 Engine Sustainability

Sustainability in engine design is usually considered as referring to the efficiency of engine operations in use, unit lifecycle costs and environmental impacts of the engine in operation. Whilst these are important aspects of the impact of engines use, there is another area of the engines industry that is under researched. The engine manufacturing plant and equipment represents a significant investment in financial, resource and energy terms. As engines have become more efficient in operation through the usage phase of their life, there has been a shift in life cycle analysis to look at production and disposal phases. Beyond the individual engine unit, consideration can be given to the sustainability of the production manufacturing equipment used to make the engine over its production life.

If an engine reaches the end of its production life prematurely, because it no longer meets market needs or is otherwise obsolete, it will not have provided the rate of return required on the investments made. High volume engines (>150,000 units per annum) are typically produced on dedicated transfer line systems for efficiency, high quality and lower costs. These production lines for machining and assembly of the major 5C components (Crankshaft, Cylinder head, Cylinder block, Connecting rod & Camshafts), are designed and manufactured to only produce one design of component of fixed dimensions. They are set up to do single machining or assembly operations and do not have flexibility to absorb changes to the dimensions of the components for which they were designed. Significant changes to the engine geometry of components to be produced on this dedicated equipment means either expensive refits that incur downtime and further investment cost that must be amortised, or premature scrappage of the equipment, so that it can be replaced by more suitable tools.

Issues of sustainability of production equipment are valid as it represents an investment of energy and materials that should be optimised as much as possible.

1.5.2 Financial Issues

Investments in engine production equipment are made on the basis of amortising those costs over the total volume of engines manufactured. Changes to that plan caused by premature end of life for the engine family means that the original business case for investing in the project may not be realised. At the very least, lifetime potential return on investment will be negatively affected.

A simplified return on investment calculation has been used in this research study to evaluate the impacts of design capacity for geometric change. This helps inform strategic decision on manufacturing equipment and align this with manufacturing process strategy to maximise the financial sustainability of the organisation.

1.6 Use of Biological Models

It is the contention of this thesis that the evolutionary processes of fitness and dynamic change in nature are analogous to the challenges facing product designers in dynamic market conditions. Bio-mimicry is the science of seeking inspiration from nature to solve human problems, whether this be direct copying of features and mechanisms, being inspired by shape and form, or adopting processes for decision making and optimisation, such as genetic programing.

This thesis seeks to use concepts from nature such as satisficing rather than optimising, to strike a balance between resource utilisation and capacity for adaptation to changing environments. The theory of adaptive landscapes which provide a means of visualising adaptability, will be applied to engine concept design to develop engine architectures that have extended production life and better use of resource investments.

1.7 Introduction Summary

The introduction chapter has outlined the context for the need for a full lifecycle plan for engines' programs. It has shown the high investment costs associated with this type of product and the challenge of defining a product at an early stage that is difficult to subsequently change, yet is under pressure from market and regulatory dynamics. The impact of premature manufacturing end of life for an automotive engine has significant financial and sustainability effects that could be avoided by more thorough planning of engine lifecycle changes at the concept stage.

Biological models of natural systems offer opportunities to consider more robust means of defining product morphology to be efficient in resource usage whilst having capacity for resilient adaptation to changed circumstances. This study will evaluate mechanisms to improve lifecycle decision making at the concept stage.

The aims of the study have been articulated, to provide a guide to bound the options considered in developing a decision-making tool for concept designers. The next chapter will provide a more complete picture of the engine design process and constraints on engine designs, and a review of natural evolutionary processes and how biological models might be usefully applied to engine design.

2.0 Context and Literature Review

The previous chapter briefly outlined the research problem and the constraints of engine concept design. This chapter provides the background context to the research question, including an overview of the engines industry and the potential for using biological models in design. The configurations of engines architectures in the automotive sector and the factors considered by engine designers in developing concepts is presented. Evolutionary developments of engine families are explained, with a review of the various strategies used by manufacturers to deal with enabling sustainable production over the lifecycle of the product. The theory of evolutionary development and how fitness criteria impact morphological development in nature is presented. Mechanisms for natural systems to dynamically match changing environmental conditions is outlined, with a review of how satisficing and resilience can be useful models for adoption for sustainable product evolution.

2.1 Introduction to Engine Design and Biological Models

This chapter provides context on engine design processes and the use of biological models, supported by relevant literature. This provides the background to understand the constraints on engines manufacturers and what drives their decision making when laying out a concept architecture for a new family of engines. Secondary sources of data on engines production and configurations have been used to establish dominant design layouts, as shown in Figures 7-11 below (IHS 2016, Suzuki 2016, Wards/Mahle 2016). An explanation of the use of secondary data is provided in the methodology section 3.4 Uses of Secondary Data. This section describes source of information used in analysis of benchmarking inputs to the engine design process. Background information on natural evolutionary processes is provided, so that it might be considered analogously as a model for optimising the change processes encountered throughout the production life of engines.

The engines industry is considered in terms of its scope and the nature of drivers for change. Requirements to meet stringent emissions targets in all sectors of the industry and economic pressures are placed in the context of competitive pressures. Typical lifecycle patterns for engines are shown with historical examples of the often-unplanned development of engine architectures once in production. The Rover K series family of engines is used as an exemplar and this will be further developed in Chapter 4 to validate the modified adaptive landscape process applied to engine concept architecture geometry decision making.

Natural evolutionary development theory, both Darwinian and Lamarckian, are reviewed. The process of evolutionary development under pressure to adapt to an environment is presented with particular reference to the influence on morphological form. From this, the theory of satisficing and resilience capacity is introduced and presented as a means of ensuring long term survival in changing environments. The adaptive landscape theory of Sewall Wright is discussed as a model for better understanding adaptability and the limits of change.

2.2 The World Engines Industry

The internal combustion piston engine, first patented in the form we would recognise today by Nikolaus Otto in 1864, has proven to be an extremely versatile means of providing rotary force to power industrial machinery, agricultural applications, motive power for transportation, electricity generation, pumping and irrigation uses, and many more applications on land, sea and in the air. The total global internal combustion engine production figures for 2008 were estimated at over 171 million units (Power Systems Research 2008).

Figure 2 shows the breakdown by application segment for engine sales for 2008. Annual sales of engines and related equipment softened after the world financial crisis of that year, but have since recovered with most estimates putting production figures and revenue in 2015/16 at approximately the 2008 levels.

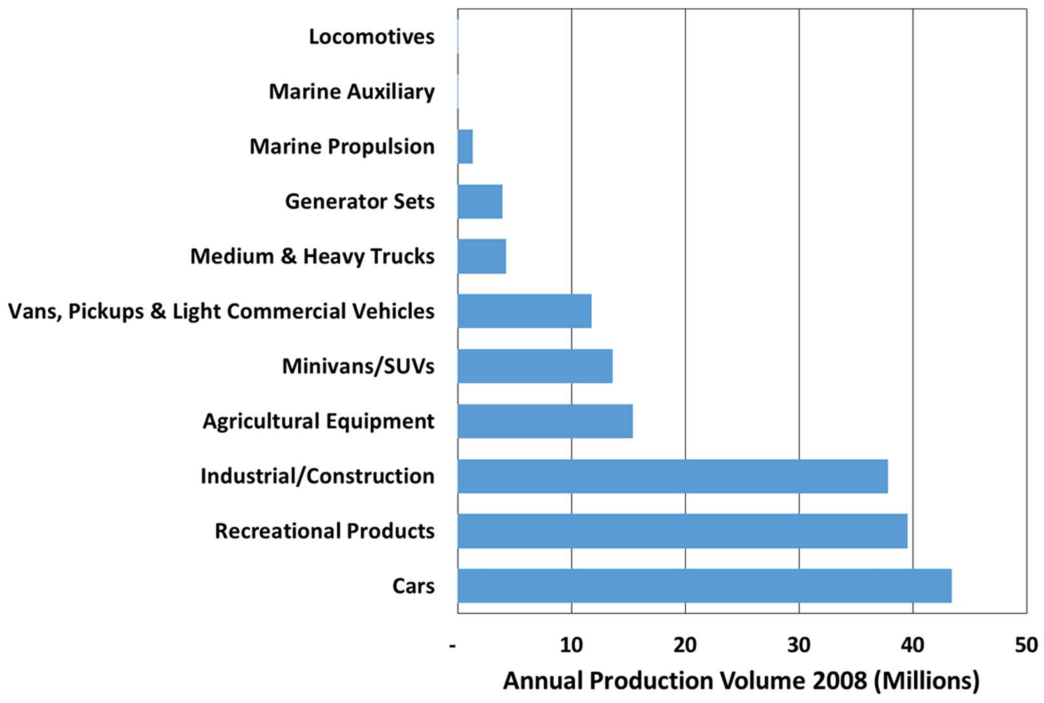

Figure 2 Annual Engine Production by Sector. Adapted from Power Systems Research 2008.

The on-highway automotive engines production volume accounts for approximately 43% of the wider engines industry that also supports the manufacture of engines for industrial, construction, agricultural and marine applications.

The engines industry is global, with manufacturers established worldwide to satisfy local market needs. Figure 3 shows the variety of powertrain fuel and configuration types favoured by different markets around the world (Bosch 2014). The selection of engine and fuel types preferred by a local market is a function of a number of factors, including:

1. Fuel availability
2. Fuel taxation policy
3. Familiarity with configuration
4. Cost considerations
5. Terrain limitations
6. Supporting infrastructure
7. Refuelling network
8. Emissions standards
9. Fuel economy considerations
10. Maintenance and service network

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Figure 3 Global Diesel Engine Usage. Bosch 2014.

2.2.1 The Automotive Engines Industry

The global automotive engines industry was estimated to be worth $194Bn in 2015, employing over 425,000 people (IBISWorld 2016). This includes all of the revenue from engine sales to original equipment manufacturers (OEMs), as well as aftermarket spares and support (IBISWorld 2016). According to the E*conomic Facts* section of the OICA (Organisation Internationale des Constructeurs d'Automobiles), the automotive industry is the single greatest engine for economic growth in the world and would be the sixth largest economy in the world if it were a country (OICA 2017).

There is a large element of 'fashion' and familiarity bias in what might be acceptable to a market in terms of engine types. An example of this is the marked disparity between take-up rates of diesel engines in passenger cars in the USA & Europe (Rankis, Simpkin & McGrath 1997). Similar differences exist for other features of engine configurations such as the market take-up rates for valvetrain types (e.g. overhead camshafts, bucket tappets, numbers of valves/cylinder), acceptance of pressure-charging systems such as turbo-charging and supercharging, and displacement preferences (the swept combustion volume of the engine, often referred to as the 'size' of the engine e.g. 1.6 litre engine).

The global market for automotive engines has recovered from the downturn of the 2008 global economic crisis, but is now facing a new challenge with a shift to newer forms of configuration with varying degrees of electrification (hybrids). Figure 4 shows annual light duty vehicle production in key markets with a projection for the next five years (Saddington 2012). A review of these types of engine predictions shows them often to be overly optimistic with the rate of market adoption estimated for new powertrain types typically falling short of expectations (Blackburn, et al. 2011). However, the trend to wider adoption of alternative forms of ICE (internal combustion engine) powertrains has accelerated in recent years, particularly the take-up of hybrid powertrains (Schreffler 2017). Growth in key developing automotive markets is showing some signs of softening, as an initial buying surge in China and Russian due to a growing middle class, combined with the availability of cheap financing, is becoming sated.

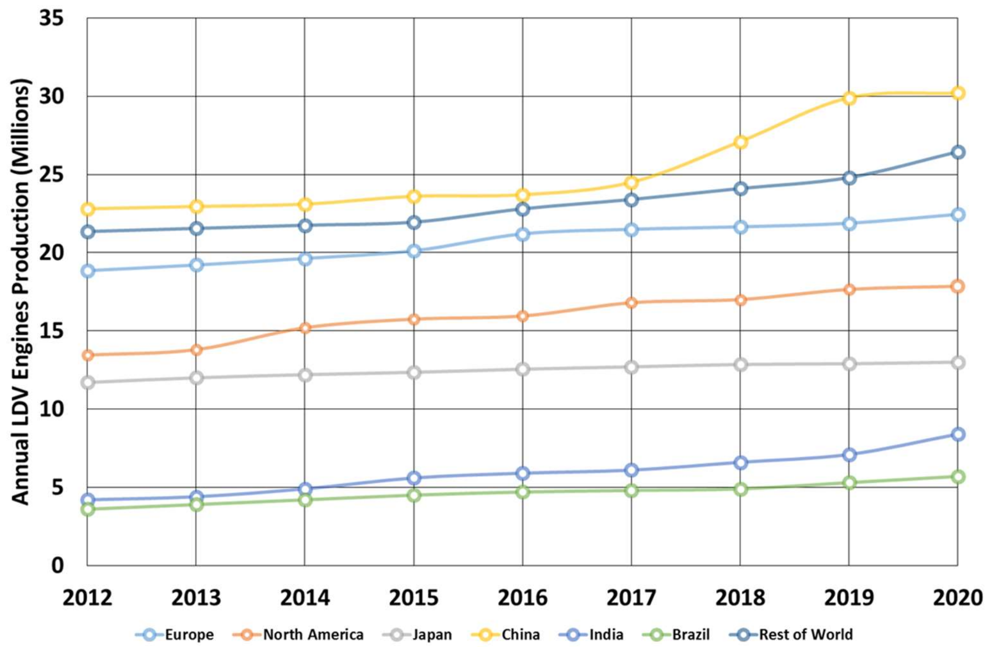

Figure 4 Global Engine Sales Forecast. Adapted from Saddington 2012.

Forecasts by IHS (2015) show a continued growth over the next several years, for automotive production, but levelling out somewhat after 2020, as key markets become saturated. This is a reflection of increased urbanisation, leading to congestion and demographic shifts in the desire for car ownership amongst younger generations (Ross 2014).

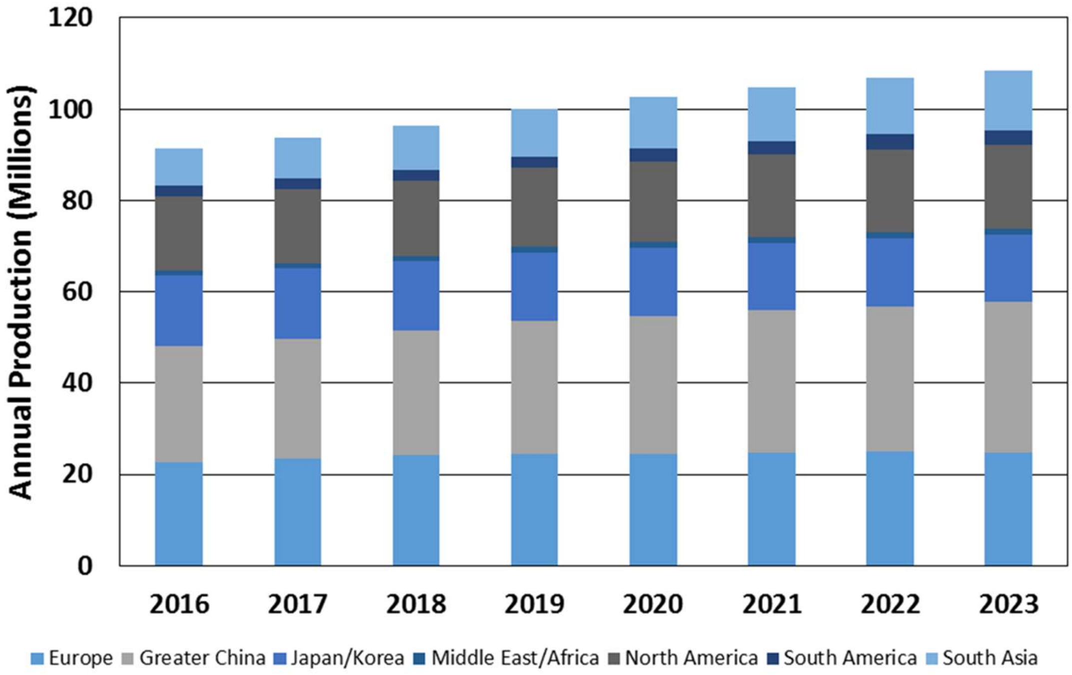

Figure 5 Global Engine Forecast. Adapted from IHS 2015.

The automotive industry is going through unprecedented change in the adoption of technologies and product configurations for powertrains (engine, gearbox and driveline systems), driven by legislation and an increasingly strict regulatory environment for low emission, fuel efficient vehicles. Although still dominated by the traditional internal combustion engine, vehicle propulsion systems are increasingly adopting varying degrees of electrification, through hybridisation to battery electric power sources (Schreffler 2017). Other advanced propulsion technologies, such as hydrogen fuel cells, continue to be developed on a trial basis but are still possibly a decade or more away from scale commercial availability.

Predictions of the take-up rate for alternative automotive powertrains have proven consistently over optimistic over the last 10-20 years. This includes all the estimates from government (Committee on Climate Change 2013, BERR & DfT 2008) and research institutes (ERTRAC 2012, Weis, Patel, Junginger, Perujo, Bonnel & van Grootveld 2012), as well as from sources that might be considered partisan (AEA/Ricardo 2009). Despite government incentives to transition to low-carbon transport and manufacturers launching an increasingly wide range of options for alternative powertrain vehicles, take up remains at stubbornly low levels, albeit increasing in recent years.

Figure 6 shows one such forecast published by The Economist in 2013, with a projection of light vehicle sales by technology type produced by the International Energy Agency (IEA 2011). Typical of this type of projection, it shows a widening diversity of powertrain technology solutions being adopted in the future. This scenario is little disputed by experts, as powertrain solutions become more nuanced to suit the needs of particular applications and customer requirements. Although remaining a very adaptable power source, the days when a single ICE piston engine type could suit all needs are disappearing as it becomes increasingly difficult to achieve legislative requirements for energy usage and emissions (Schulte & Wirth 2004). What is more difficult to predict is the rate at which this change will occur. The automotive industry is quite conservative in its product offerings, not least because of the enormous costs involved in getting a product decision wrong. The slow rate of market adoption of some of the newer configurations of powertrains suggests that the buying public may be just as conservative.

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Figure 6 Engine Technology Forecast. The Economist/IEA 2013.

The drivers for change to vehicle propulsion systems, led by government, has created an explosion of technical solutions and options for propulsion units not seen since the early days of the car at the end of the 19th and beginning of the 20th Centuries. Despite this development, it is likely that the conventional internal combustion piston engine will remain dominant as a power source for road transport for many decades to come. The vast industry that supports the manufacture of engines and their components will therefore remain an important part of the economy for the foreseeable future.

The major automotive companies are currently fending off competition from domestic producers in China, India and other regions with high growth, as well as upstart challenger companies, such as Tesla Motors in the USA. It remains to be seen how long the incumbent automotive manufacturers can hold on to their traditional dominant positions. Although it moves slowly, the automotive industry is in a continual state of flux regarding the position of the major players and the location of the heart of the industry and has been since its inception over 130 years ago when Karl Benz developed his first car. The current position of manufacturer brands in the USA is shown in Figure 7 (Wards/Mahle 2016).

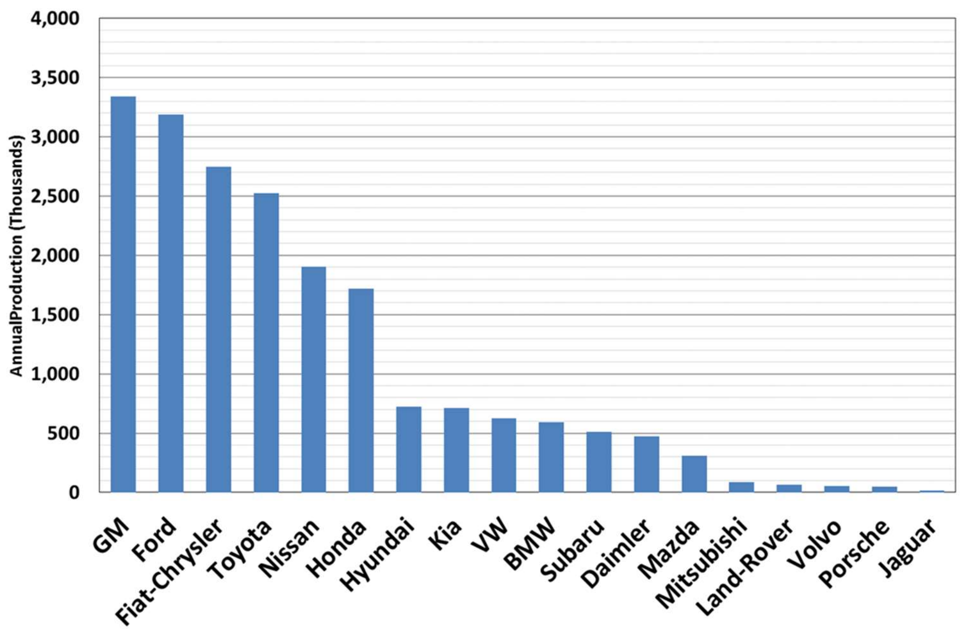
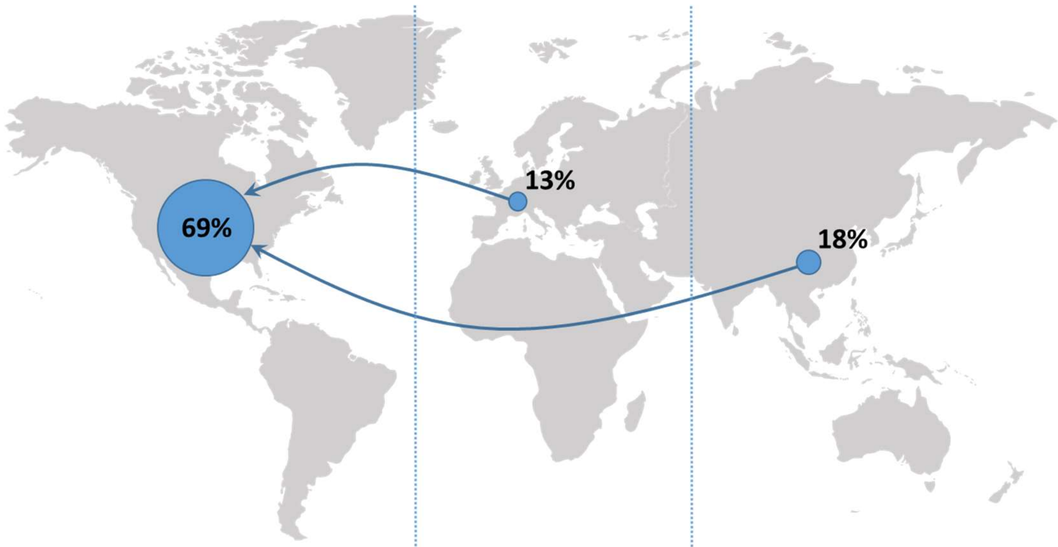


Figure 7 US Engine Sales. Adapted from Wards/Mahle 2016.

Some measure of how global the automotive and engines industry is can be gleaned from Figure 8, which shows the source of engines for automotive applications in the USA market. Local annual production from within the USA (8,901,885 units) only accounts for 45% of the total product sold within the US (19,639,768 units) and is a reflection of the global nature of engines supply (Wards/Mahle 2016).



Americas		Europe		Asia	
USA	8,901,885	Germany	1,192,200	Japan	2,037,750
Mexico	2,857,300	Austria	589,800	South Korea	1,221,150
Canada	1,748,600	Spain	330,550	Australia	171,450
Brazil	100,900	UK	241,900	Thailand	18,200
		Italy	103,483	Taiwan	4,500
		Romania	73,500		
		Sweden	36,500		
		Hungary	10,100		

Figure 8 US Engine Source. Adapted from Wards/Mahle 2016.

2.2.2 Engines Configurations

The common configurations for engines follows the pattern of the Zipf Law. First proposed as a guide to patterns of statistical distribution in the social sciences, it has since been shown to have relevance for describing a natural law of distribution in areas as diverse as the frequency of the use of words in language, populations in cities, and earthquake prevalence, to the location and size of ore and oil deposits (Merriam, Drew & Schuenemeyer 2004). Related to forms of geometric distributions such as Pareto and Bode's laws, Zipf-like distributions' utility is in their ability to enable us to look at a pattern of members of a finite set, identifying the dominance of particular values and allowing concentration on the most important sectors to enable efficient operation. Engine designs follow a Zipf law pattern in that engine layouts are dominated by a limited number of configurations. Figure 9 shows an analysis of the categorisation of global automotive engine displacements derived from secondary data on world automotive engines (Suzuki 2016, 2014). Note that the chart is ranked in order of the number of engines of particular displacement categories.

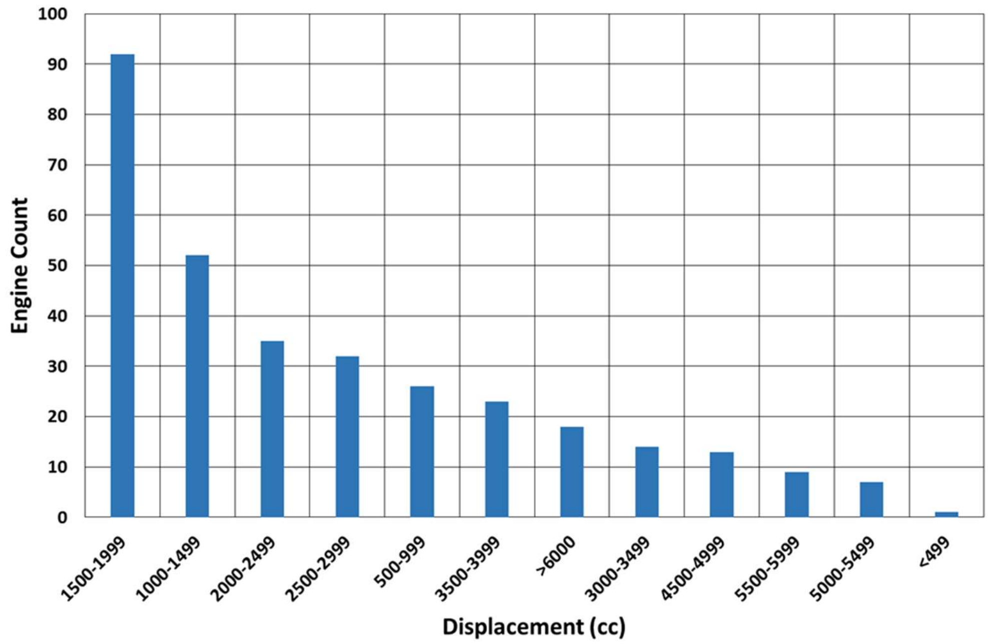


Figure 9 World Engine Displacements. Adapted from Suzuki 2016.

A similar analysis of the number of cylinders in global automotive engine configurations in Figure 10 shows the popularity of particular layouts (Suzuki 2016, 2014). Local markets may have some variation in this pattern, such as the USA light duty vehicle market favouring vee configuration six and eight-cylinder engines, whilst Japan and Europe favour in-line four-cylinder engines. However, even with slight local differences, the pattern remains remarkably consistent overall across different regions of the world.

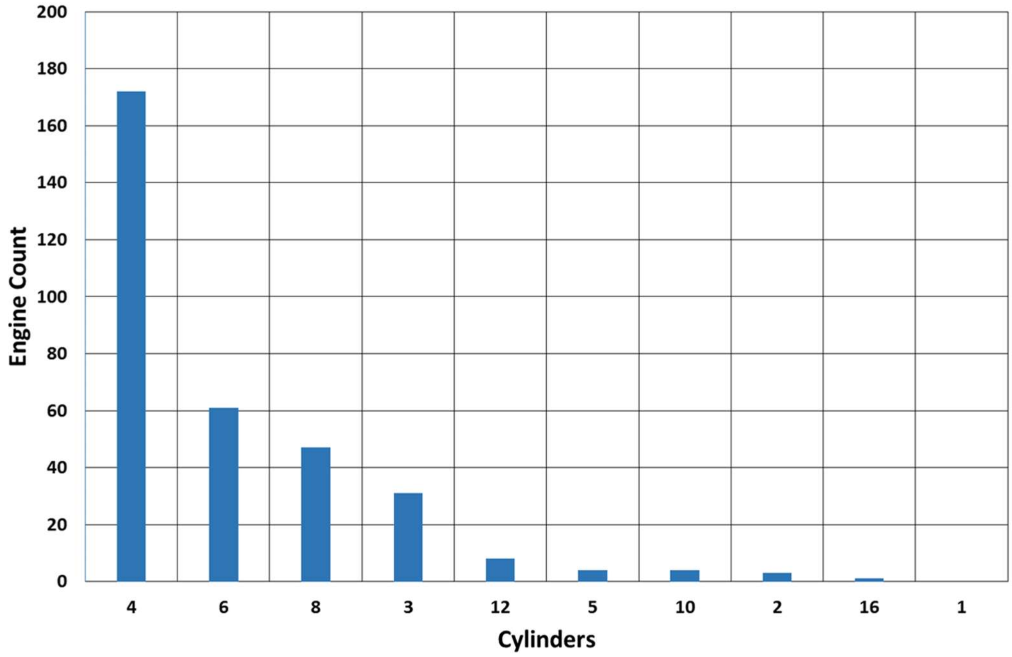


Figure 10 World Automotive Engine Configuration (Cylinder Count). Adapted from Suzuki 2016.

The data shown in Figure 11 gives an indication of the shifts and changes in the configurations of engines for the US market, projected out to 2023 (IHS 2016). This allows us to see that even the US market is dominated by in-line four-cylinder engine configurations. Market data like this is useful to manufacturers in assessing the trends in market preferences, but also in gaining an awareness about market familiarity and potential supporting infrastructure for different types of engine configuration.

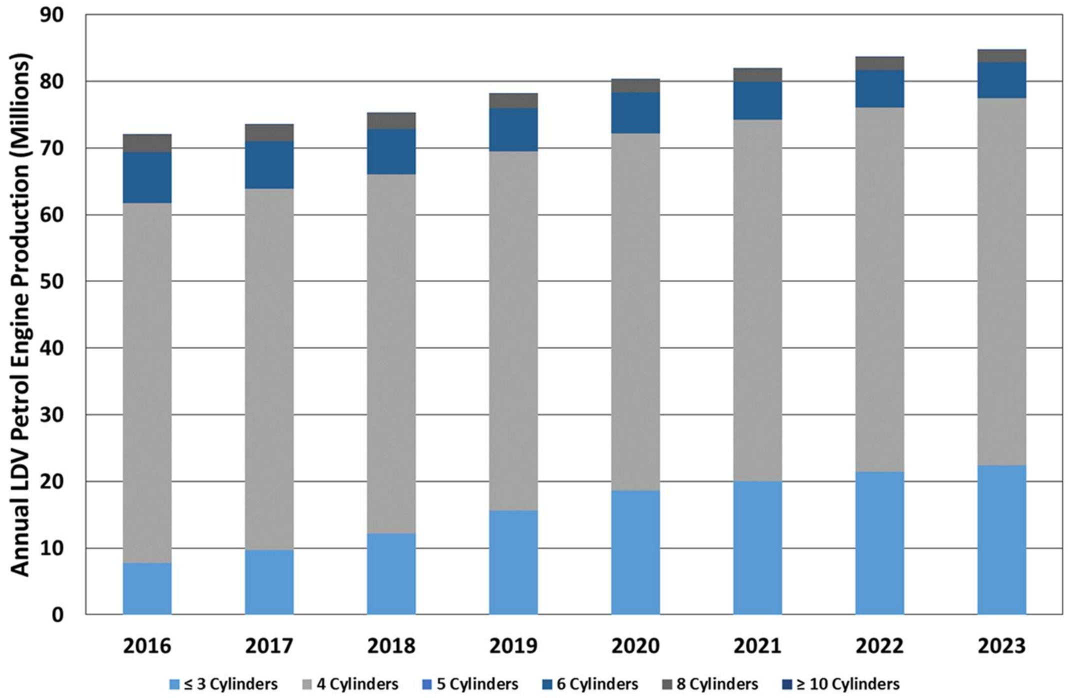


Figure 11 World Automotive Annual Light Duty Vehicle Production. IHS 2016.

2.2.3 Drivers for Change

Internal combustion engines have developed through a series of incremental changes over extended periods, interspersed with occasional step changes in technologies and configurations. This process of rapid occasional development with longer intermediate stages of gradual progression, was first described as *punctuated equilibria* by Eldredge & Gould in 1972 when looking at patterns of biological evolutionary development seen in the fossil record (Eldredge & Gould 1972). Product development follows a similar evolutionary development to that seen in nature (Ziman 2000, Mokyr 1990). Work by Eger (2013) and Ehlhardt (2016) shows how product designs follow evolutionary paths, responding to the pressures from the marketplace for selection of features and attributes. The internal combustion engine has developed over 130 years to match the needs of users and to incorporate the developments in materials, manufacturing capability, technology development and the many other changes in the operating environment that have occurred along the way. The development of engines can be seen from phases of development that have occurred at key points in their history. A review of engine performance in the early development of aero-engines (Price 2012) shows how specific power density has gone through phases that receive jolts of impetus from external factors. In the case of the early aero-engines this came from a number of sources, most prominently the pressures of war between 1915-1918 and 1939-1945.

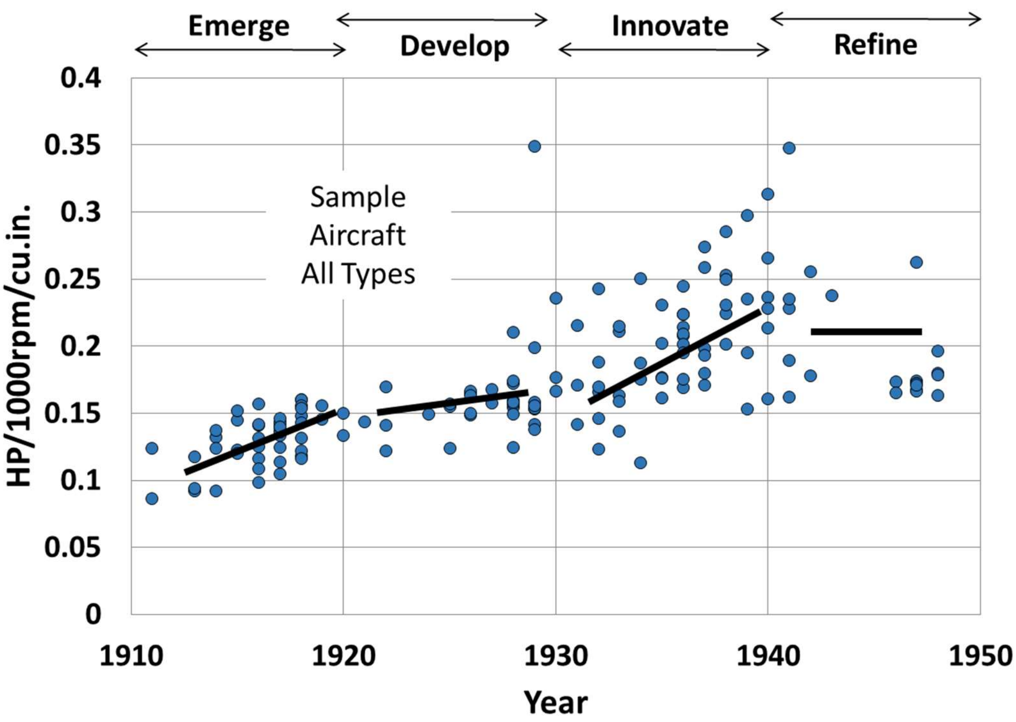


Figure 12 Aero-engine Power Density Development. Price 2012.

Over the period indicated by Figure 12, there were also government sponsored competitive programs and private racing series, such as the Schneider Trophy, which did much to spur on development of high performance engines. Outside of these periods of intense external pressure, where there is a premium placed on achieving high performance in a few specific characteristics such as weight or speed, there is a tendency for designs to converge to a limited set of solutions that meet the needs of the majority of the market whilst limiting the extent of variety. This approach allows for economies of scale to reduce costs, as well as enabling better product support through standardisation. A reduction in variety allows for lower cost maintenance and service through commonality of spares and easier service technician training. Figure 13 illustrates this evolutionary development of designs with the example of the development of bicycle frame design over time. The evolutionary nature of bicycle design as an illustration of the progressive development of product design forms has been explored by several researchers, including Lake & Venti (2006).

Figure 13 Divergent and Convergent Bicycle Design 1860 to 1980. Roy 1983.

The pressures on engine manufacturers to improve their products have never been more intense. In addition to the normal desire of any product manufacturer to continually improve their product offering and remain competitive in the marketplace, engine manufacturers have the additional challenge of operating in a highly regulated industry. Whilst not being unique to the engines industry, the degree of regulation applied for emissions, safety and efficiency has been unprecedented over the last 30 years. Figure 14 shows the fall in CO2 emissions since 2000, with known commitments projected out to 2025 published by the International Council on Clean Transport (Yang 2014). Achieving large reductions in emissions requires careful selection of engine geometry to optimise combustion performance and improve engine efficiency (Manning 2012, Hoag 2006, Heywood 1988).

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Figure 14 World Emissions Compliance. Yang 2014.

Similar trends have been followed for regulated pollutants such as nitrous oxides, carbon monoxide, sulphur oxides and hydrocarbons. Compared to 1970 levels new on-highway vehicles are roughly 99 percent cleaner for common pollutants such as hydrocarbons, carbon monoxide, nitrogen oxides and particle emissions (EPA 2017). In recent years, particular attention has been paid to NOx and particulate matter, as these are closely associated with local air quality. The design of an engine's combustion chamber, including the selection of bore/stroke ratio, directly effects the formation of hydrocarbons, NOx and particulates (Hoag 2006, Heywood 1988, Khovakh 1977). The bore/stroke ratio and engine displacement together with number and arrangement of cylinders, creates the architectural configuration of an engine design. Within these constraints, the engine designer will seek a compact arrangement in order to minimise package size, weight and cost (Hoag 2006, Barnes-Moss 1973, Tresilian 1965a-i).

The USA, Europe and Japan all have strict emissions limits for IC engines. Regulation harmonisation across most other developed regions means that these standards are becoming widely adopted across global markets. Off-road applications for engines, such as agricultural machinery, industrial equipment, marine applications and domestic products that incorporate an internal combustion engine, are not immune from regulation. As an example, Figure 15 shows the emissions challenges for agricultural tractors to comply with emissions standards in Europe and the USA (John Deere 2017). This indicates the scale of emissions reduction mandated since the mid-1990s. In order to achieve these reductions whilst minimising the additional costs of after treatment systems, base engine designs have been optimised to reduce engine-out emissions. These are the raw emissions produced by an IC engine prior to exhaust treatment with catalytic converters, particulate traps, exhaust gas recirculation systems or the plethora of complex and expensive emissions compliance systems that have been developed (Folkson 2014). Further discussion of engine geometry considerations to achieve low engine-out emissions is covered in section 2.2.6 Engine Concept Design Process.

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Figure 15 Off-Highway Emissions Standards. Source: John Deere 2017.

Since the 1970's the dominant driver for engines design has been emissions regulations. First introduced in the USA for road transport, they have now been formalised in most countries around the world. The regulation of engines of all types, from small utility engines, to large ship and locomotive engines, is now the norm. Technology road maps give some indication of shifts in the likely changes to engines that will be driven by regulatory requirements, although these are usually at a high level and subject to political negotiations. Figure 16 shows the UK technology road map for automotive engines developed through industry consultation by Ricardo on behalf of the UK government (Automotive Council UK 2013).

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Figure 16 Automotive Technology Road Map. Automotive Council UK/Ricardo.

Combined with the electronic control systems introduced as part of the new emissions regulations and the improving engineering modelling techniques developed from aerospace in the 1980's, engines became more reliable and durable (Slee & Parker 1995, Fenton 1986). The quality systems trends emerging from Japan in the late 1990's reported in the seminal Massachusetts Institute of Technology (MIT) studies as part of the International Motor Vehicle Program (IMVP) and later popularised first in the US and then around the world by the book 'The Machine That Changed the World' (Womack, Jones & Roos 1997), led to wide adoption of Lean engineering techniques, quality processes and a more structured approach to process control. This led directly on to the Toyota Production System and similar approaches becoming the operating norm within the automotive manufacturing industry (Ward, et al 1995).

One of the key tenants of the Toyota Production System (TPS) is minimising variety. A ruthless drive to eliminate the possibility for variation in production processes is seen as a mechanism to reduce the possibility of deviation from an accepted standard. A highly structured and disciplined approach to process ensures that as far as is practicable, all aspects of an operation are fixed (Sobek, Ward & Liker 1999). In *Dynamic Economics*, Klein discusses the need for flexibility in an operation (Klein 1977). Citing analysis of firm's survival, Klein shows that highly structured firms or those that are unstructured, are less able to survive the dynamics of most market and operational conditions. A capability to react dynamically to changing circumstances is essential to an operations long-term survival and relies on building in a degree of diversity and flexibility in a company's structure and its operations (Klein 1977). An overly optimised design is inflexible to change and in a dynamic environment where requirements are uncertain over time, this limits the potential life of a product configuration. We can see that there is a tension between the desire for low product variety and change driven by the Toyota Production System to keep costs low and ensure consistent quality; with the need to be responsive to potential uncertain market dynamics and the need to maintain a competitive product configuration, fit for purpose.

Customer expectations for product quality have also increased over time. Customers are no longer tolerant of the poor reliability and functional quirks that they might have had to put up with 30 years ago. New entrants to the European and US markets from Japan and South Korea in the 1990's differentiated themselves in the market and helped establish their brands, by offering enhanced powertrain warranties as standard (Levin 2015). Initially warranties for 2-3 years specifically for powertrains, these quickly morphed into 5-year, 10-year and eventually lifetime powertrain warranties as both the incumbent manufacturers and the new brands competed to match each other's offers.

Other aspects of engine design, including fuel consumption, safety, heat output, noise and end of life disposal are now also regulated, requiring careful decision making by the engine designer to achieve a balance of requirements with the selected engine architecture. The desire of end users for products that are reliable, compact, lightweight and low cost has not diminished, placing pressure on designers to 'satisfice' multiple criteria. A concept originally postulated by Herbert Simon in 1959 in relationship to achieving optimal economic investment, this is further explored in section 2.2.5 related to engine design and sections 2.3.4 in the context of adaptive landscapes (Simon 1997).

A survey of engineers involved in the design and development of engines was conducted by the author - see section 3.3 Engine Designer Interviews for an explanation of the methodology used to produce this data. From the survey, key challenges for engines programs were identified. These are summarised in Figure 17. The pressure to be fast to market was indicated as the primary driver for engineers working on new engine programs. Interestingly, their perception of the need to achieve a return investment was low, second only to the challenge of dealing with people issues on projects. Engineering teams can be very focused on the technical aspects of engine design and development, spending relatively less time and energy on business issues. This can have a direct impact on considerations of investment choice in the plant and equipment that will be specified for production of the final engine design.

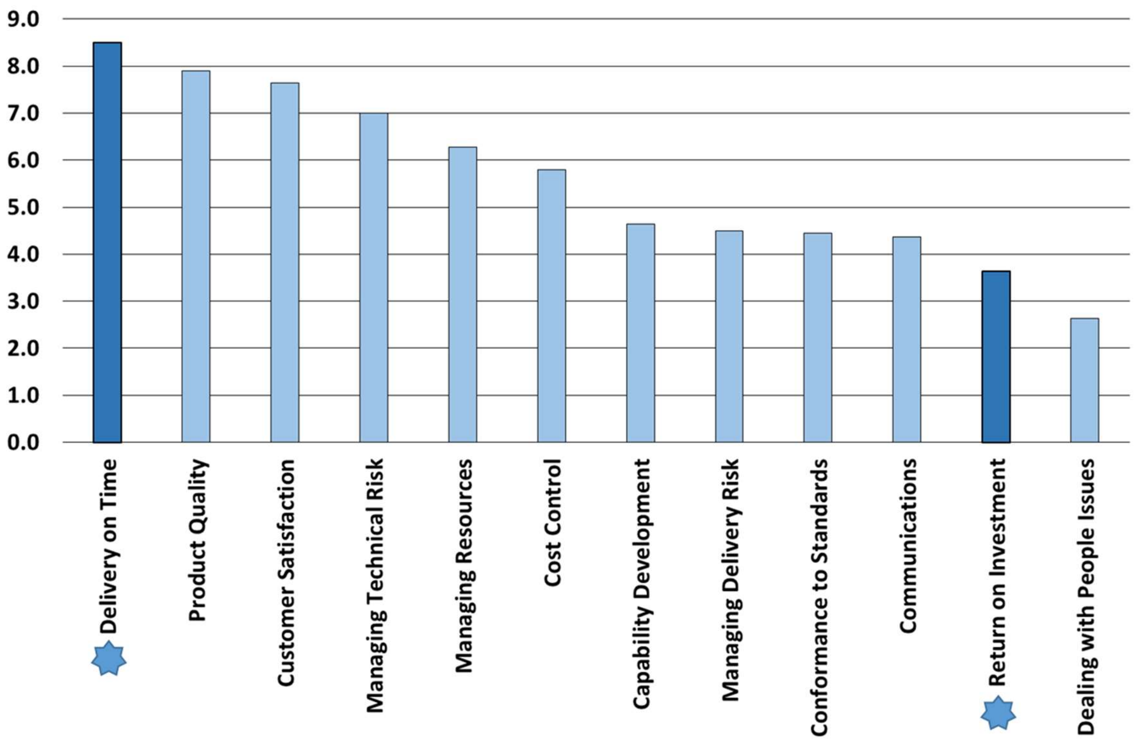

Figure 17 Drivers for Engine Programs.

In certain market segments, a narrower band of tolerance for satisficing is possible due to the need to be competitive with product performance. An example of this are race and high-performance applications, where other design criteria such as cost and ease of service may become secondary to performance and weight. Figure 18 shows the engine evolution for the production road version of the Suzuki GSXR 750 motorcycle from 1985-2010. Influenced by the race variants of this product, road versions are subject to more rapid change than less high-performance derivatives, as they are positioned as flagship products in the market. The changes in bore/stroke for the engine are shown related to major engine design changes to remain competitive. Intermediate with these major architecture changes, the performance development of the engine can be seen tracked above the bore/stroke changes. Updates and upgrades occurred almost every year to keep the product fresh in the marketplace for what is a highly competitive niche in the motorcycle industry. All of this design effort was expended for product that has annual worldwide sales in the region of only 17,000 units. This figure was constructed from Suzuki product specification data sheets from 1985-2009.

Figure 18 Suzuki GSXR750 Evolution.

An example of a high-performance sports car engine change cycle can be seen from an analysis of Porsche engine production figures for the long-lived 911 product (Frere 2002). Figure 19 shows an average of only 2.8 years for the production life of a variant, defined by a unique bore/stroke combination. In reality, there was a lot of component and sub-system sharing between these engine variants, so that economies of scale can be achieved at a component and system level, if not at a complete engine level.

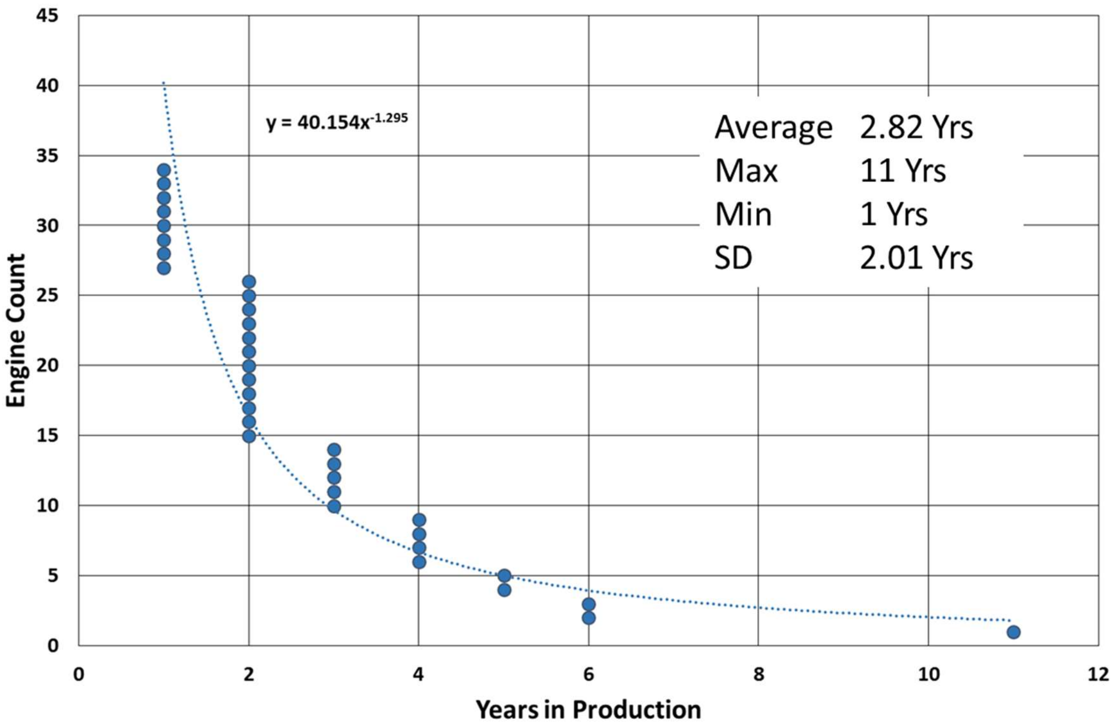

Figure 19 Porsche 911 Engine Production. Adapted from Frere 2002.

It may appear that these engines would struggle to be financially viable with relatively small volumes and rapid change. However, it is perhaps because they do have small volumes that the manufacturers have invested in flexible machining centres to produce these engines. Combined with ‘soft tooling’ for castings and forgings, that has a much shorter life than ‘hard tooling’ used for higher volume, but also correspondingly lower cost, the production and tooling investment set up is amenable to rapid and continual change. This provides an opportunity for regular updates to engine designs that are not so constrained by fixed equipment. The downside to this flexibility is that it creates a logistical problem of managing variety, both in production, and the dealer network for spares and service. This is explored further in section 2.2.5 which discusses alternative strategies for investments in engine production planning

2.2.4 Engine Lifecycle Considerations

The cycle of development from conception, through creation to operation and finally end of life, is akin to the lifecycle of a biological entity. The concept of a product lifecycle can be applied to the production life of a particular engine configuration or family of engines. This extends from the conception of the engine design, through its engineering development into production, to the end of its production life when it is no longer manufactured (Asiedu & Gu 1998). More often however, lifecycle cost analysis (LCCA) refers to primarily economic considerations of the selection, purchase, operation and disposal of an individual unit (Girardi, Gargiulo & Brambilla 2015). Although there is no consistent or agreed scope for what stages and elements are included in lifecycle cost analysis, the most comprehensive analysis of unit whole lifecycle costs might consider energy and material usage from extraction of ore, through the purchase, production and usage phases, to disposal, recycling and back to ore (MacLean & Lave 2011, Taemichi & Yoshida 2001). What is less often considered is the lifecycle of the supporting and ancillary equipment involved in production. The tools and equipment that are used to make products, are of course a product themselves. In the case of engines manufacture, the production lines and equipment that are dedicated to machining and assembly, form a major part of the costs of the product and heavily influence the overall business case for a return on investment required to justify a project (Wortmann & Alblas 2009, Smith & Keoleian 2004). For high volume engines, these are dedicated equipment, designed and manufactured solely for the production of one product. The production life of that product therefore determines the required life of the production equipment. There is an after market for old, dedicated engine production lines, but it is limited and cannot be relied on to extend the life of this investment as there are too many uncertainties concerning demand (Liu, et al. 2014, Smith & Keoleian 2004).

There may be a host of different lifecycles that are nested into one another at various levels:

- **Product Unit Lifecycle** - The life of an individual unit, such as a single engine. This is usually the main focus of lifecycle costing analysis (LCCA). The principal consideration is on the usage phase, but this is increasingly looking at production and disposal to gain a more complete picture of a unit's lifecycle.
- **Product Variant Lifecycle** - A single variant or version of the product will be made for a period of time, such as a particular displacement of an engine e.g. the 2.0 litre version or a turbo-charged version of a family of engines. This will require some unique tooling, but will heavily utilise existing equipment for manufacture that is used for the main family of products. It will also share many common components to other members of the product family.
- **Consumable Tooling Lifecycle** - Consumable tooling is used over the life of production, so that dies, cutting tools, fixtures and jigs, may need to be refurbished and replaced at regular intervals throughout the production life. This is a factor of volume, unlike the production equipment which has effectively infinite life by comparison.
- **Product Family Lifecycle** - This defines the period over which all variants of a product are made.
- **Production Lifecycle** - The production equipment may be adapted to make several families of product over time. In the case of high volume engines production, machine tools are usually designed to be dedicated to one family of engines and are economically written off over that period.
- **Technology Lifecycle** - Technologies usually have longer lifecycles than products or the production of a family of products. However, a change in technology may interrupt the lifecycle of a production line or range of products if the technology goes obsolete during the production period.

This study is concerned with extending the useful life of the heavy capital investments made in engine production lines by extending the production life of the engine architectures manufactured by that equipment. Any extension of the useful life of production equipment will have a positive impact on not only the economic business case for the original investment, but will avoid premature disposal of assets and resources, thereby improving the sustainability impacts of resource utilisation.

The production of an internal combustion piston engine (ICE), is a major commitment of time and resources (Daniels 1997, Suzuki 1997). A typical ICE program will take 3-4 years of engineering effort from concept generation to product launch, involving a team of 50-500 engineers and product developers (Hoag 2006, Holt 2005, Dopson, Taitt & Sandford 1995). A study by the Motor Industry Research Association (MIRA) in 1997 put the cost of a new automotive engine program at an average of $557M, including engineering, tooling and equipment costs (Rankis, Simpkin & McGrath 1997). This cost can be further broken down as approximately 15% engineering, 26% supplier tooling, 8% OEM consumable tooling and 51% fixed machine tools and supporting infrastructure to manufacture the engine core components. It is now common practice for engine OEM companies to outsource almost all component manufacturing to a tier 1 network of specialist suppliers (Caputo & Zirpoli 2002). Indeed, many of the components and systems, such as engine management systems, seals, fasteners and sensors, will be standardised components, designed and developed by the suppliers and offered to a range of OEM companies as off-the-shelf components (Manning 2012). Other suppliers will design, development and manufacture key systems, such as piston, head gaskets and valves, that may be beyond the technical capability of most OEMs to manufacture (van Basshuysen & Schafer 2004). However, OEM organisations generally keep control of those base engine components that make their engine configuration unique and are used as the architectural framework of the engine. These are sometimes referred to as the 5C components - Cylinder block, crankshaft, cylinder head, camshafts and connecting rods shown in Figure 20 (Daniels 1998).

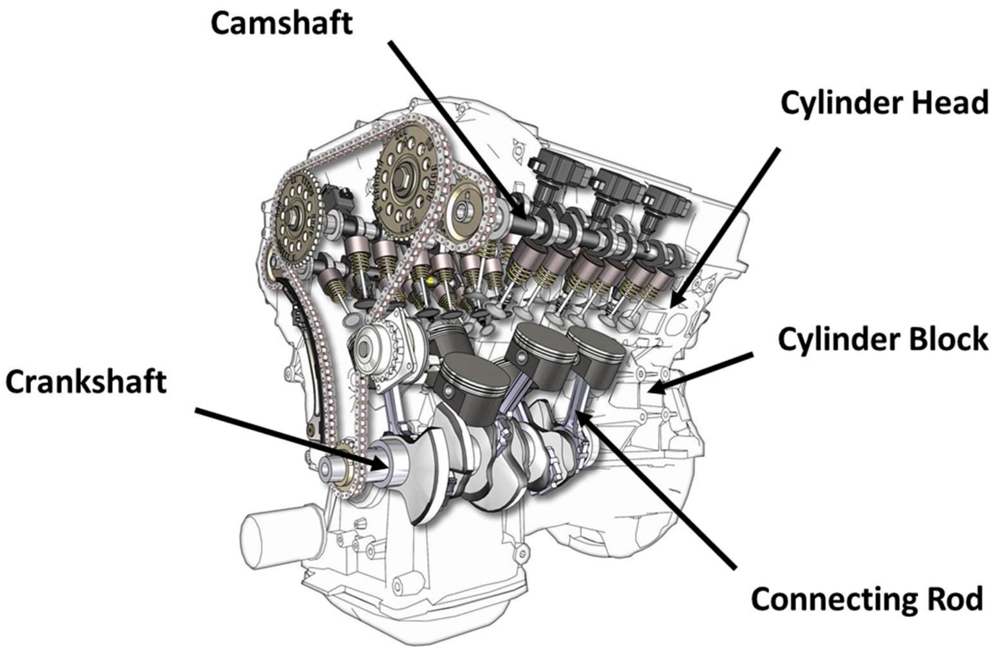

Figure 20 Engine 5C Core Components.

An analysis of the world automotive engines plant data published by Automotive World 2013, shows the production volume of an average automotive engine plant is in the region of half a million units per annum for light duty vehicles (cars, vans) and 130,000 units per annum for heavy duty vehicles (trucks, buses) (Automotive World 2013). Table 1 shows the range of production volumes for automotive engine plants around the world, from very low volume specialist suppliers, typically for sports car and super luxury products, through to high volume engines that may go into a range of vehicles, possibly shared between different manufacturers.

	Light Engines	Heavy Engines
Max	1,915,567	600,652
Min	1,000	10,437
Average	441,546	132,192
SD	371,312	114,357
Total	62,257,994	5,552,058

Table 1 World Engines Plant Annual Production. Adapted from Automotive World Engine Plants 2013.

Each engine plant will typically produce a range of engines, whose individual volumes can be estimated to be in the region of 170,000 units per annum based on data from engine family production figures (Daniels 1997). A report by Jeff Daniels for the Economist Intelligence Unit provides information on automotive engine families and the volumes in which they are produced. Although estimates vary, it can be seen that the production volumes involved in typical automotive engines require a large investment in plant and equipment to support production to the required quality level over an extended period. High volume production processes are required to get efficient plant operation, as this allows for consistent production manufacturing processes with minimal set-up and tooling changes. To gain economies of scale over an expected production life of 10-15 years, plant and equipment must be robust throughout the production life and exhibit reliability and durability. Table 2 shows the annual production figures for an indicative range of engines families, across 244 engines variants from 34 manufacturers (Daniels 1997). This gives us an idea of the scale and scope of engines manufacturing in the automotive sector.

	Light Engines	Heavy Engines
Max	1,915,567	600,652
Min	1,000	10,437
Average	441,546	132,192
SD	371,312	114,357
Total	62,257,994	5,552,058

Table 2 Typical Engine Production. Adapted from Daniels 1997.

One of the most significant challenges faced by engines manufacturers is the rapid rate of change in the sector, driven by the increasingly stringent regulatory environment on emissions and fuel economy, as well as by the demands of the market place (Daniels 2008). There has been worldwide over capacity in the automotive industry for the last 10-20 years, which gained a short reprieve for established manufacturers through the early 21st century with the opening up of the so-called BRICs new markets (Brazil, Russia, India, and China) (Trivedi 2017). A softening of initial demand as these new markets became saturated, combined with the rise of more domestic producers in these regions, has put increased pressure on established firms to be efficient (Bryant 2012). Automotive companies run at very tight net profit margins, with many making only 1-3% on sales. This restricts re-investment and means that all assets must be as highly utilised as possible to make a return on committed investments already made (Yang 2014).

A review of engine production databases (Wards/Mahle 2014, Autodata 2013, Sankaido 1999) for a range of engine types was used to establish the context for typical engine production life across application types (Price 2015a). Table 3 shows the range in production duration for engines in use for industrial applications, such as large generators and small marine, light duty automotive applications, motorcycle applications and utility engines used for generator sets and irrigation pumps.

Table 3 Typical Engine Production Life by Application.

Engines databases (Autokatalog 2016, Autodata 2013a-c), were used to establish the expected production life of automotive engines. Figure 21 shows the data for automotive diesel light duty vehicles worldwide. The average production life is 8.5 years, but can extend up to 29 years. Each of the variants considered represents a major architecture (bore/stroke) and may be part of a family of engines that share components, in production across a longer period. This may explain how some of the engine variants are only apparently in production for two years, as it would otherwise prove not to be economically viable to invest in development and tooling for such limited production.

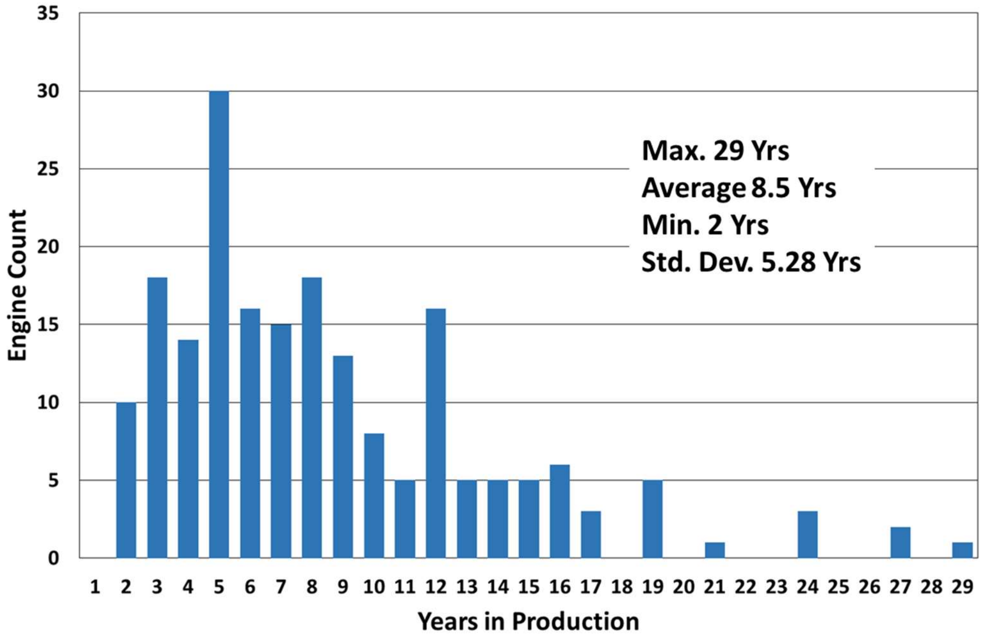

Figure 21 LDV Diesel Engine Production Life.

Comparative data on gasoline engine variants is shown in Figure 22. The average production life is 8.8 years in this case, comparable to that of the diesel engine data. A marked skew of the data toward shorter product life is evident in both the gasoline and diesel data, with a long tail distribution to the right for a smaller number of long lived engines. This is a further indication that engine production equipment needs to be flexible to cover potential uncertainties with eventual production life (Routley, Phaal & Probert 2011, Koste & Malhorta 2000).

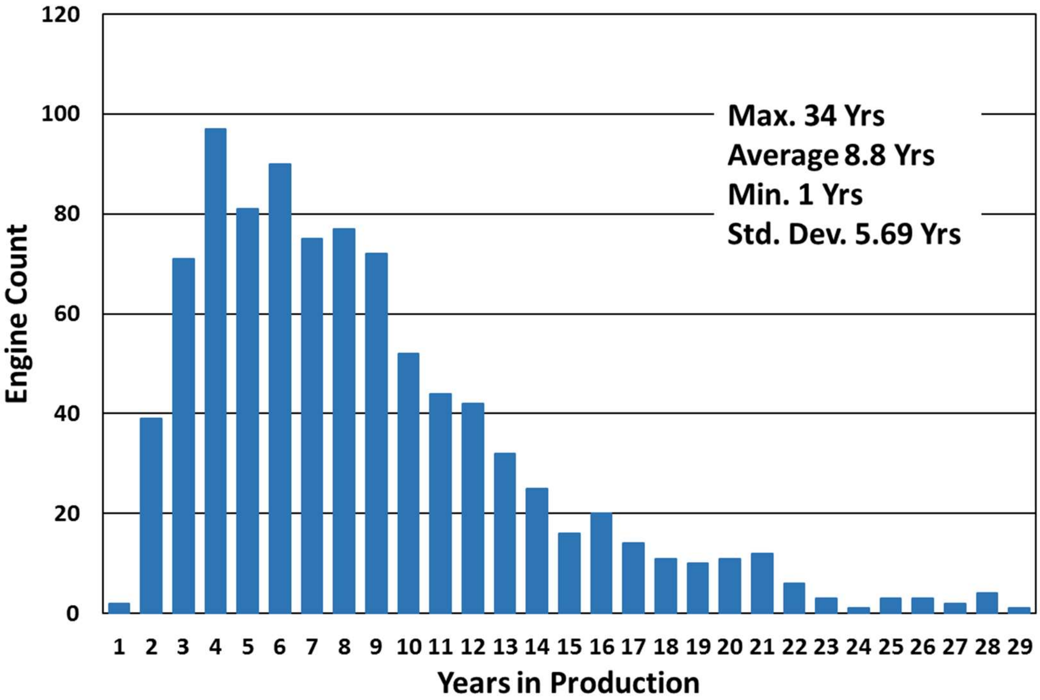

Figure 22 LDV Gasoline Engine Production Life.

The data was selected to show engine production lives that are complete, i.e. the engine has gone through the complete cycle to end of production life. Engines currently in production have been excluded, as their eventual total production life is currently unknown. An example from another application is motorcycle engines, which tend to have a shorter production life than car engines. This is primarily due to the nature of the market for motorcycles which has a strong emphasis on absolute performance and is highly influenced by fashion trends and marketing through race series. The data shown in Figure 23 is drawn from Autodata information on how long motorcycles were available in the European market. This indicates an average production life of only 5.4 years (Autodata 2013).

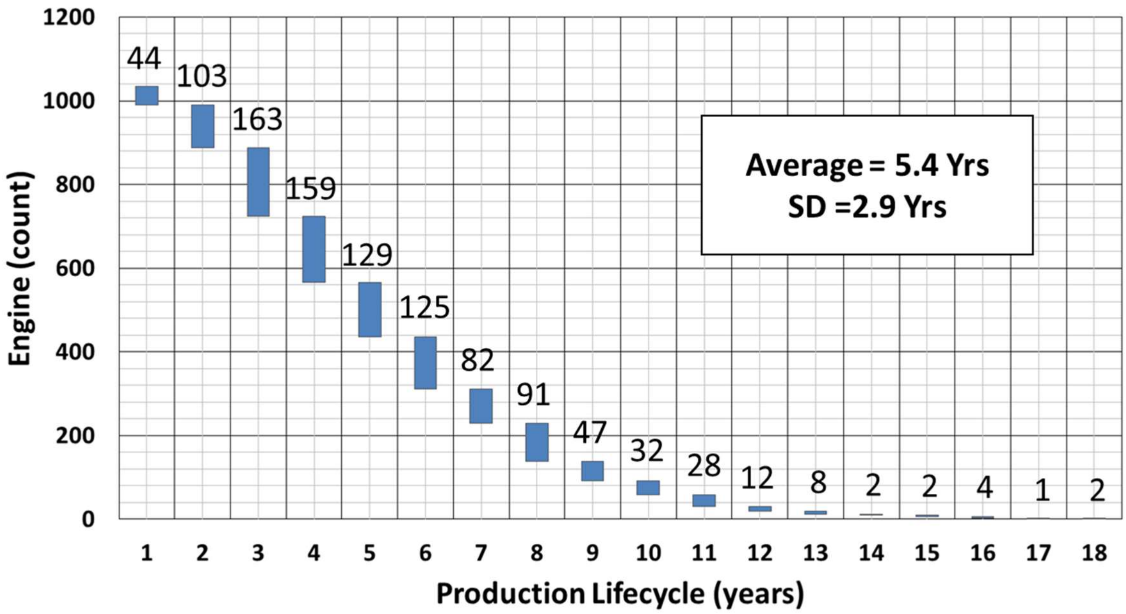

Figure 23 Motorcycle Engine Production Life. Adapted from Autodata 2013.

Figure 24 shows the theoretical product production life for a typical engine. The product will go through a period of design and development involving investment in resources and the initial tooling costs for production. During this period investment costs accrue as expenditures are made in advance of sales. Once production starts there can start to be a return on the investments made as sales revenue offsets the prior investments and any current costs incurred. Eventually a break-even point is reached when total cumulative income exceeds total incurred expenses. Excess profit beyond this point can be returned to investors for reinvestment in following projects or taken as a dividend.

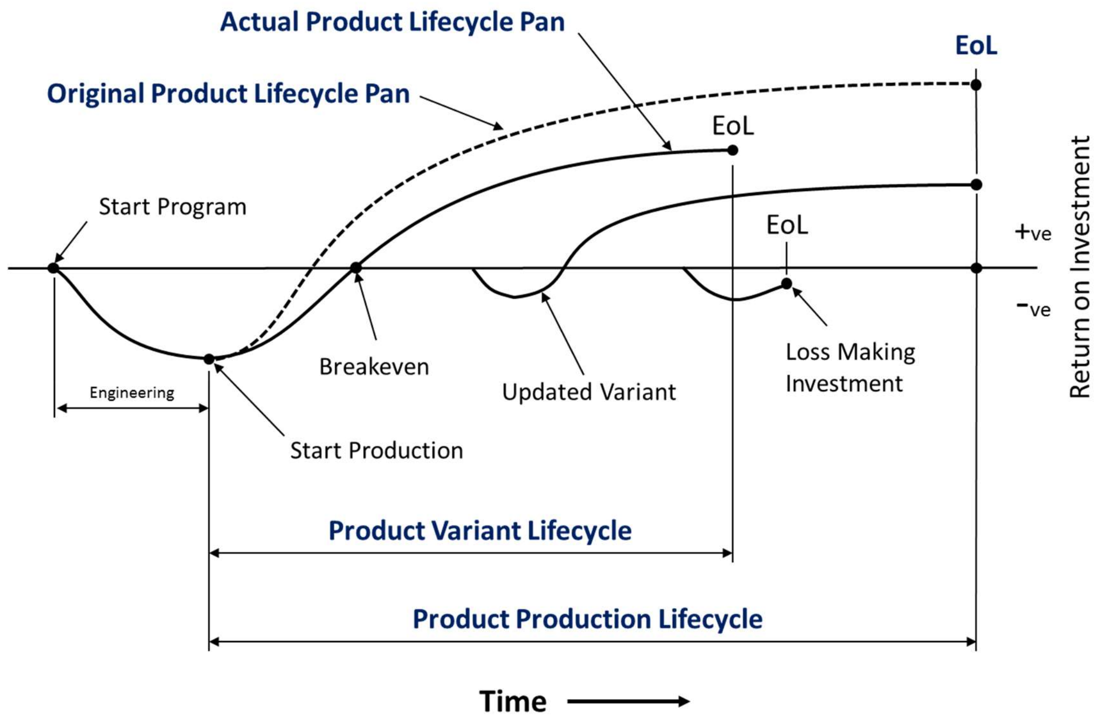

Figure 24 Product Lifecycle Variants.

The actual rate of return may vary from the plan depending on how well the product has been accepted in the marketplace. Eventually, the product variant will have diminishing sales as the market becomes saturated and it succumbs to competition. The product will reach a natural end of life point and be discontinued from production. During the life of the first variant, as sales diminish, consideration will be given to other variants or replacement product. Due to the heavy investments made in production equipment there will be pressure to reuse or otherwise utilise the existing equipment (Yang 2014, Haynes 1997, Fine & Li 1987). This may put severe constraints on what is possible with the design of the next variant, as there will be a desire to maximise the return on the investments already made in production tooling and equipment (Liu et al 2014, Koste & Malhorta 2000). It would be hoped that variant planning is done at the concept stage, so as to have a structured lifecycle plan for the entire product family over its expected lifetime in production (Wortmann & Alblas 2009, Norton & Bass 1987). Given the vagaries of the marketplace and the extended time over which engines products are in production, it is not always possible to know what variants may be required in advance. Note that each new variant will require its own investment for engineering, tooling and launch costs. Some variants may not succeed in the marketplace and may never return the investment made.

The longer a product family can be in production, the greater the return on that investment. Taking all investments for variants together, Figure 25 illustrates the impacts of production life. If the usage of existing production equipment can be extended by even a few years, it can have dramatic effects on the level of return on the investments made. The high investment required in capital equipment for engines production and the long life of the product in the marketplace, compared with many other products, makes this particularly challenging. End of life (EoL) at an idealised lifespan in the marketplace (EoLγ) provides the maximal return on investment. Sales are gradually diminishing as the market become saturated and interest moves to newer products, possibly provided by competitors. A premature end of life (EoLα) may be encountered when the product is not accepted by the marketplace, possibly due to an unsuitable specification, quality/brand issues or other issues that damage initial market take-up. A product which exits the market at EoLα has not been able to recover its investment costs and fails to make any profit for the business. A reduced production life (EoLβ) may be encountered due to the product encountering a change in technology, legislative restrictions or other external factors than mean that despite sales potential the product must be withdrawn from the market. This results in a reduced lifetime profit for the product and an underutilisation of the production tooling and equipment. Production life calculations can be uncertain and are subject to dynamic change (Oguchi & Fuse 2015), but use of historical data can give us a basis for planning, to understand the sensitivity to investment decisions.

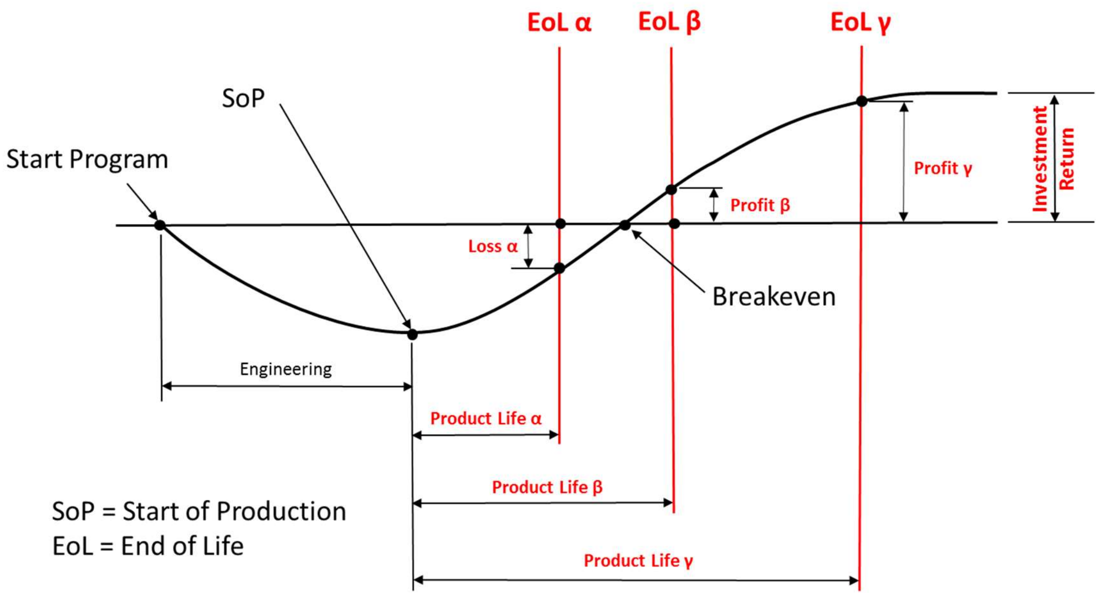

Figure 25 Production End-of-Life Effects.

Historical Engines Developments

The planned production lifecycle of an engine is subject to many external pressures, such as competition from other firm's products, regulatory changes, the influence of fuel prices of buyer's choices, trends in buyer preferences and a host of other factors outside the control of the product planner. In planning a more realistic expected lifecycle, it is useful to review some examples of similar engines life histories, to gain an idea of the potential deviations that may be encountered. This gives us a representative exemplar for us to analyse potential sensitivities to changes in demand for any new planned product.

Engines can go through quite complicated lifecycles that might not have been envisioned when the original engine concept was laid down. To illustrate some of the more extreme extended production lifecycles, we can look at two examples of engines that went through significant engine architectural changes over an extended period - The Coventry Climax family of racing engines and the Miller-Offenhauser race engine family.

The Coventry Climax

The first example engine is the Coventry Climax range of racing engines developed in the 1950's (Hammill 2004, Hassan 1975, 1966). The original concept for a light weight, high power output engine was to satisfy the need for a fire pump engine initially for forest fire fighters and subsequently for other fire services that needed a portable, high output pump. Figure 26 shows the original four-cylinder FWP/FPE (fire water pump/fire pump engine) design done by Walter Hassan for Coventry Climax in 1952/53.

Figure 26 Coventry Climax FPE Engine. Hammill 2004.

The design used the best technology available at the time to produce a lightweight, compact engine. After the initial success of the FPE engine in its first applications, Coventry Climax sought other potential markets for the engine (Hassan 1975). The Coventry Climax company went on to develop the engine for use in on-road automotive applications and as a marine outboard engine. For each potential new application, the design of the engine was adopted to suit its new requirements. The base engine design of the combustion chamber and valetrain configuration was carried across to new variants as much as possible. This approach was taken to build on the performance development success in current applications. Inevitably, each new application had its own constraints and requirements for engine size (displacement), performance output, package size, weight, features, cost constraints, etc. This resulted in some significant changes in configuration from changes to bore/stroke ratio, number of cylinder and intake/exhaust packaging differences, through to different cylinder arrangements from the original inline cylinder configuration to vee and flat engine configurations (Hammill 2004). In each embodiment of the engine, much effort was put into carrying across as many features and design elements as possible (Hassan 1975). This approach of gradual evolution allowed the designers to build on prior success, reduce development time and reduce risk.

The attributes of the engine were ideal for racing applications and it was soon developed as a racing engine for a range of formula (Hammill 2004). Figure 27 shows the many applications of the base engine design. Although it was reconfigured into different arrangements to optimise the design for each particular niche need, using varying numbers of cylinders and covering a range of displacements; each variant of the engine had a direct lineage to its predecessor. This illustrates the complex evolutionary path often followed in engines design and although the Coventry Climax range is notable for the number of variants eventually produced, their significant deviation in form and configuration, it is typical of the process of evolved paths engines often follow through their developmental and production life. Figure 27 illustrates the design connections starting from the original FWP engine (circled), through the engine family's various incarnations. Race engines are indicated by black, automotive applications by green, fire pump engines by red and marine applications by blue. Certain variants were used in multiple applications, hence the use of multiple colours in some instances. The number and arrangement of cylinders are shown, together with the displacement of each variant.

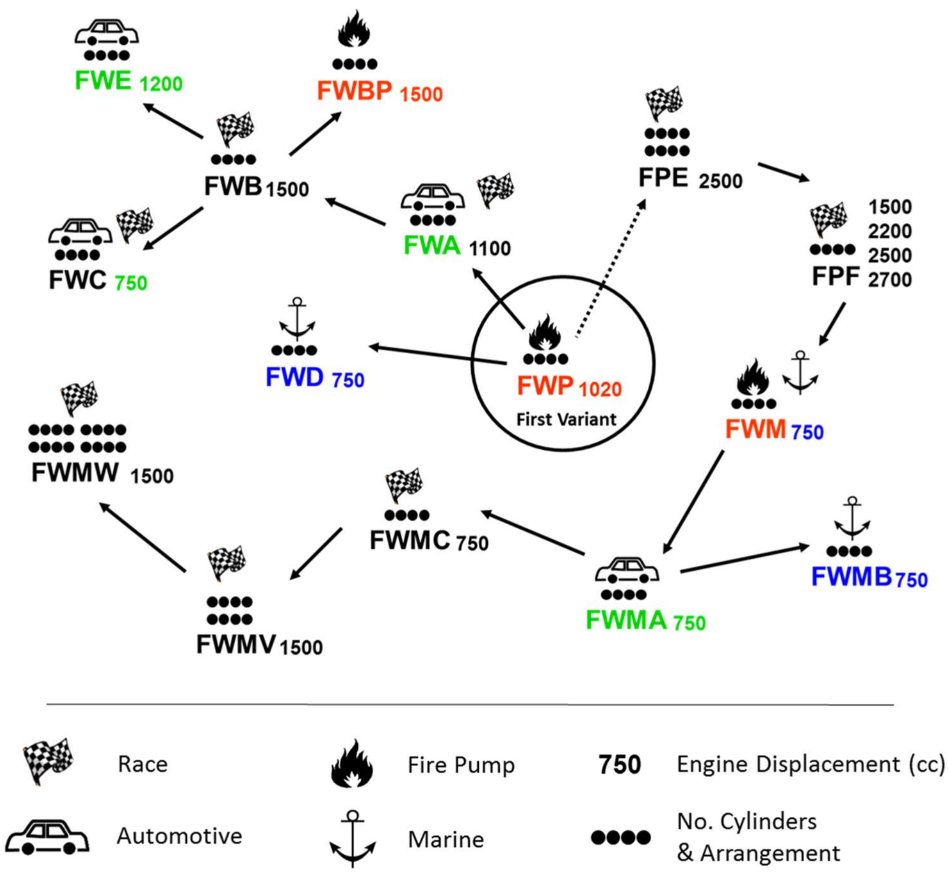

Figure 27 Coventry Climax Engine Evolution. Adapted from Hammill 2004 & Hassan 1966.

The V8 racing variant used in Formula 1 went on to be one of the most successful racing engines of all time, second only to the Cosworth DFV engine for racing success (Hammill 2004, Blunsden 1983). It is a measure of both the optimisation of the design for high performance and low weight that the design was so successful in the highest levels of motorsport. The era in which the Coventry Climax engine was used by F1 teams was also a period that saw a significant emphasis placed on power/weight ratio to drive high performance on the track. This favoured designs that used smaller displacement, higher revving engines with good breathing for rapid combustion. These traits picked up on the four valve/cylinder, pent-roof combustion chamber, double overhead camshaft arrangements first seen in racing and aero-engines of the 1920s, most notably the Peugeot Gran Prix racing engines of 1912/13 (Cameron 2012, Borgeson 2002, Gunston 1999, Bingham 1998, Whitney 1998, Hack & Indra 1997). This has become the most common engine combustion chamber/valvetrain arrangement for not only race engines (Bamsey 1988a/b), but latterly for on-road automotive applications (Manning 2012, Saddington 2012, Rankis, Simpkin & McGrath 1997).

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Figure 28 Coventry Climax V8 Racing Engine. Hassan 1966.

The Miller-Offenhauser

The Coventry Climax is by no means alone in having such an extensive development history or long production life. The Miller-Offenhauser four-cylinder racing engine has a similar developmental path (Ludvigsen 2001, White 1996). Over a period of more than 50 years from 1934, the engine was developed for racing in a number of track racing formula, primarily in the USA. Once again, these various incarnations of the engine, based on the original design, evolved to better meet new needs. Features, configurations and components were carried across from earlier generations of the engine in order to reduce risk, minimise component and development costs and build on prior knowledge. This illustrates the evolutionary nature of successful designs, that simultaneously seek to adapt to new requirements whilst minimising change.

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Figure 29 Miller Racing Engine. White 1996.

Development of the Miller/Offenhauser continued under various corporate banners with Drake, Miller and Offenhauser being the most well know. Produced in a range of displacements, the base engine structure and layout remained constant over that period. This example illustrates how once engine designers land on a configuration and arrangement that works well, they are loath to depart too much from that plan, even though they may need to make adaptations and changes to suit a particular application. Figure 30 shows how the power density of the engine has evolved over time to maintain the competitive edge of the engine (Holt 2005, White 1996, Mantel, Rosegger & Powell Mantel 1995). This evaluation uses a metric of horsepower per unit displacement (cubic inches in this case) per 1000rpm of engine speed. This metric is a way to nominalise performance relative levels across engines of different displacements and maximum engine speeds.

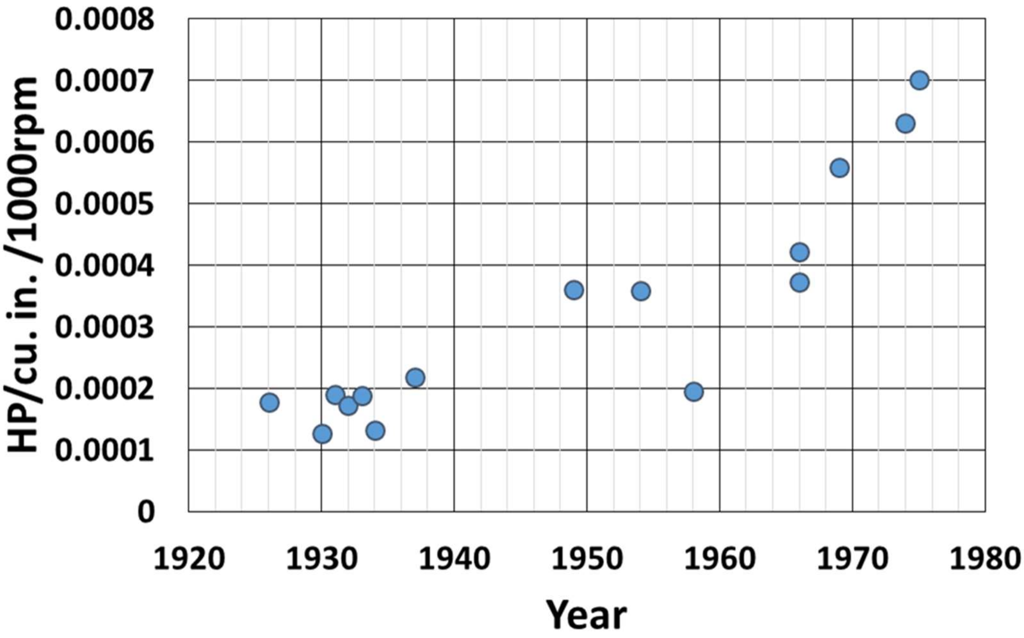


Figure 30 Miller-Offenhauser Development. Adapted from White 1996.

Rover K Series Engine

Production engines are no less susceptible to the need for variants of existing engines, whilst wanting to minimise change to investments in existing tooling and equipment. The engines industry can be quite conservative in making changes due to the heavy investments required (Hill, Edwards & Szakaly 2007, Haynes 1997, Bjorkman 1995, Weitzel 1973). The automotive sector has a particular challenge in this regard, as it faces one of the toughest regulatory compliance environments and operates in a market of fierce competition with minimal margins (Daniels 1997, Rankis, Simpkin & McGrath 1997).

An example of how engines seek to optimise a range of variants at the concept stage, but then get overtaken by events over time, is the Rover K Series engine. This was a four-cylinder engine manufactured by the Rover Group from 1989-2005. The engine subsequently became part of the assets acquired by the Nanjing Automobile Company (NAC) in 2006 upon the demise of the Rover car company.

The engine was developed in the 1980s during a period of economic recession and shortly after the fuel and energy crises of the 1970s. The particular economic and regulatory challenges during this period led to a strong emphasis on fuel economy and efficiency in the product designs coming out of the automotive industry. This was also the first generations of engines that were being designed after the imposition of emissions regulations into major markets, such as USA, Europe and Japan. Although only aimed at the European market, the design decisions made on the Rover K Series project were influenced by factors effecting the whole industry (Stone, et al. 1990). The concept design was therefore very focused on being compact, lightweight and fuel efficient. The product planning departments at Rover, then part of British Leyland, sought to optimise the engine specification from the start. The engine was designed to be optimised for two configurations - a 1.1 & 1.4 litre engine with two and four valve per cylinder options for different performance levels (Hiljemark, Knight & Shillington 1990, Stone, et al. 1990). The engine was optimally designed around these displacements, with minimal material usage and a compact size. This led to it being best-in-class for weight and power density at launch.

A key feature that allowed for weight reduction was the use of a 'long-bolt' arrangement. In a conventional engine, the cylinder head bolts pass through the head and into the top of the cylinder block. These important components take all of the combustion loads from the engine as well as often taking structural loads from engine mounts and other engine ancillary loads from front end drive systems. The cylinder block is then independently bolted to the crankcase or bedplate of the engine, which resolves loads from the crank drive system. These forces, whether from the cylinder head or bedplate, are transferred into the cylinder block as a tension load. The block is therefore highly loaded in both tension and compression, as it also acts as the main mounting platform for most engine accessories, such as starter motors, alternators, power steering pumps, air conditioning compressors and any other engine systems components. These loads are in addition to its primary function, which is to contain the cylinders and the absorb piston and combustion forces. This presents a problem for aluminium cylinder blocks, which are relatively weak in tension. Relatively large sections of cast material must be provided around the threaded areas of the block to adequately deal with bolt loads. This is exacerbated in die cast components, which not only require thinner walls to suit the casting process (acceptable solidification times), but also generally produce lower tensile properties than other forms of casting. In the

Rover K Series inline engines, the cylinder head bolts were designed to pass through the block, creating a clamped ‘sandwich’ of layers from the cylinder head, block and crank bedplate (Hammill 2009, Hiljemark, Knight & Shillington 1990). This innovative design reduced the loading in the cylinder block, as it was no longer resolving combustion forces through threaded sections, being entirely held in compression. This allowed for thin-wall castings of the major components, significantly reducing weight. An additional advantage was improved bore distortion of the cylinders, leading to less blow-by of combustion gases, improving fuel consumption and emissions performance.

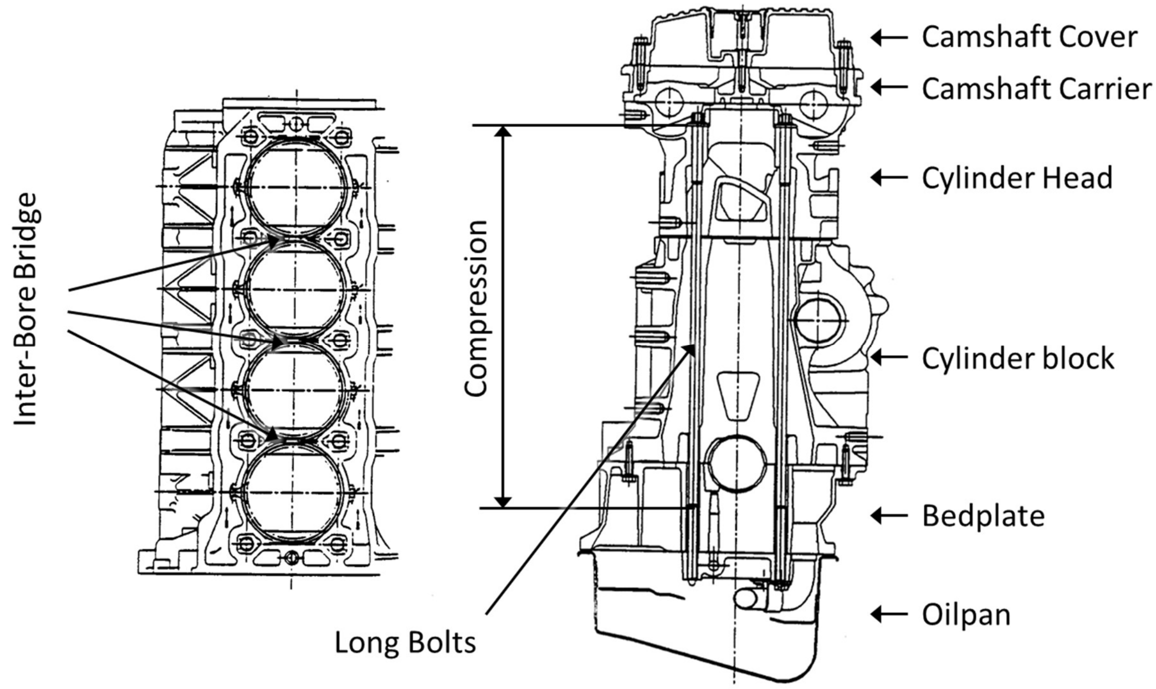
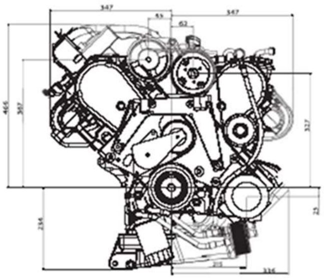


Figure 31 Rover K Series Head Bolts. Adapted from Hiljemark, Knight & Shillington 1990.

The long-bolts were placed as close to the bores as possible to reduce package size and weight. Spacing out the bolt centres would mean reduced clamping forces at the bore, which would necessitate higher loads and more material around the block to stiffen the structure. The closer the cylinder head bolts are to the bore, the more efficient the design in terms of weight and size. However, the disadvantage of this close package is that it does not leave room for expanding the bore at a later date. The bore bolt spacing is a crucial fixed design geometry point in engine designs (Manning 2012, Hoag 2006, Mackerle 1972). During the production life of the engine there was a need to grow the displacement of the K series engines to create new variants to meet new market needs for higher performance and for application to larger vehicle categories. The engine displacement was expanded by increasing both bore and stroke to create a 1.6 & 1.8 litre variant of the inline engines. As the engine had originally been optimised for a 75mm bore, these versions of the engine compromised the cooling around the cylinder. Normal coolant flow between the cylinders is essential in minimising bore distortion and maintaining an adequate seal between cylinders. The cylinder head gasket is a crucial component in maintaining this seal and relies on the cylinder head bolts having sufficient clamping load for the gasket to seal effectively. The K series engine design initially had a wet liner arrangement, where coolant freely flows around the cylinders. When the bore size was increased from 75mm to 80mm, the long bolts could not move out a corresponding amount, as the spacing and pitch of the bolts was locked in to the existing production line equipment (Hammill 2009, Hiljemark, Knight & Shillington 1990). This type of design geometry constraint is not uncommon in engines. Indeed, fixed equipment geometry for manufacturing and the implications of cascading changes throughout the engine initiated by bore or bolt centre changes, were the primary reason why early Rolls-Royce V8 engines maintained the same bores for over 40 years, despite much evolution of the rest of the engine and a constant need to improve performance (Grylls 1963). The design of the Rover K series cylinder cooling was changed to a so-called 'damp' liner. In this arrangement, the space between bores is to too small for free flow of coolant but efforts were made to allow for nucleate boiling of coolant in a narrow passage drilled in the inter-bore bridge area to perform some thermal management. The thermal load on the cylinder bridge area was further thermally stressed by later developments of the engine that incorporated variable valve control and turbo-charging.



	L4				V6	
	1.1	1.4	1.6	1.8	2.0	2.5
	2V/4V	2V/4V	4V	4V/VVC/Turbo	4V	4V
Bore (mm)	75	75	80	80	80	80
Stroke (mm)	63	79	79	89.3	82.8	66.8
Bore Bridge (mm)	13	13	8	8	-	-
Bore Centers (mm)	88	88	88	88	-	-
Weight (kg)	85	85	90	90	145	145
BHP	60/75	75/103	116	120/160	150	190
	Original Design					

Figure 32 Rover K Series Dimensions.

The stresses on the inter-bore area led directly to cylinder head gasket issue, which became the Achilles heel of the K series (Hammill 2009). Although multi-layer steel gaskets were developed to cope with this situation it was not uncommon for 1.6 & 1.8 litre variants to have head gasket failures at 60,000 miles, giving the engine a poor reputation for quality. Over 20,000 engines were replaced under warranty for head gasket failures and an unknown number were affected outside the warranty period (Hammill 2009). This illustrates the severe limitations placed on engines growth potential by early decisions on engine geometry. The engine designer seeks to optimise the engine geometry for efficiency with known engine configuration requirements on the original concept layout. However, these geometry design choices mean that future growth potential or geometry changes for uncertain or currently unknown requirements may be excluded.

The K series engine was produced on a dedicated transfer line machining system for both the cylinder head and cylinder block machining. This was part of a 5C (**C**rankshaft, **C**amshaft, **C**ylinder head, **C**ylinder block, **C**onnecting rod) production capital investment of over £200M made by Rover to produce the K Series family. Further investments were later required for the V6 version of the engine which was produced as a 2.0 & 2.5 litre engine. It is worth noting that the V6 engine carried across many of the features and components of the original L4 version including the combustion chamber and valvetrain arrangements. However, as it was a vee configuration it could not take advantage of the long-bolt arrangement. This was because the bolts would need to cross each other in clamping two banks of cylinder heads bolted to the same block at an angle of 60 degrees between the banks. This would have been an extremely complex arrangement for assembly and was not considered practicable for high volume production (Hammill 2009). It could therefore be said to have had all the constraints of the original design and none of the benefits, especially of the weight reduction enabled by long bolts. This type of evolution away from the original fitness peak on the design landscape, is by no means unusual. Indeed, it occurs so frequently in engine life-histories that it can be thought of as the norm. An original design is laid out with certain variants in mind and the product eventually goes on to be evolved in directions that were not anticipated (Weertmann 2007, Hooper 1999a,b). In most cases however, a review of past history and more careful consideration of the likely whole lifecycle of the product might have provided the insights necessary to see that other options will probably be required. Although not all options would be captured in this way, as foresight is never perfect, it would help to alleviate the worst of the disruptions and mitigate expensive capital write-off prematurely.

The expansions to the Rover production line to accommodate V6 and diesel variants were catered for by the addition of flexible machine tools inserted in side lines to the main production transfer line system. In addition to the extra costs of these lines, it meant that the flow of materials through the line was now no longer optimal. Figure 33 shows the K series production line for block production. The extent of tooling investment and the fixed nature of geometry can be gleaned from this image.

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Figure 33 K Series Production Line. Hammill 2008

Figure 34 shows the production life of the variants of the K Series engine. Some 2,500,000 L4 (inline four cylinder) engines were manufactured, with an additional 140,000 units of the V6 engine variant. A diesel version was made with nearly 420,000 units produced in total. One important point to note is the changes of ownership of the company over the production life of the engine series. The design activity was started when British Leyland was under government control. It was therefore the British government that was in the position of approving the considerable investments required for a new engine, something they had been reluctant to do but were eventually persuaded was required by the British Leyland board and supported by the Ryder report on the investment requirements to keep British Leyland a going concern, presented to the UK government in 1975 (Hammill 2009, Ryder 1975). Ownership passed to British Aerospace in 1988. British Aerospace were somewhat reluctant buyers, having been pressured by government to assist a policy of privatisation. The British Aerospace era was marked by a culture of asset stripping and minimal investment. BMW bought the Rover group in 1994 and made greater investments in plant and equipment. The growth of engine variants can be seen during this period as BMW sought to utilise the resources of Rover and fit these brands within a coherent automotive strategy. Something British Aerospace lacked the foresight or will to do. The expansion of the engine range was something already planned by Rover. Now with the resources and support of BMW they were finally in a position to make it happen after a protracted period of uncertainty and under investment (Gould 2015, Hammill 2009). By 2000 Rover had transferred into private equity ownership under the Phoenix Consortium. Once again, a period of minimal investment ensued that saw the gradual decline and demise of the brand. After several failed attempts to sell the Rover Group and its assets as a going concern, the company entered administration in 2005. The remaining assets of the Rover group, including all intellectual property for the K Series engine and its production equipment which was at the time a separate company called Powertrain Ltd, passed to Nanjing Automobile (NAC) in 2006. Nanjing themselves were acquired by Shanghai Automotive (SAIC) shortly after in a struggle between these companies for ownership of the Rover assets. SAIC currently owns the rights to the engine and has continued its development, albeit in small production volume, to the present time. The ownership of the engine and therefore the approvals for investments and development, have passed through six different owners over the products production life. Each owner has had very different business objectives and levels of expertise and resource that could be brought to bear on the product. Each has sought to maximise the utilisation of existing plant and equipment investments that they have inherited and this has placed a significant constraint on what was possible in terms of further development of the product and how long its production life could be extended. Figure 34 shows the development of K series engine variants over the major part of its volume production life, from initial launch in 1989 through to the end of high volume production with the MG Rover group going into administration in 2005.

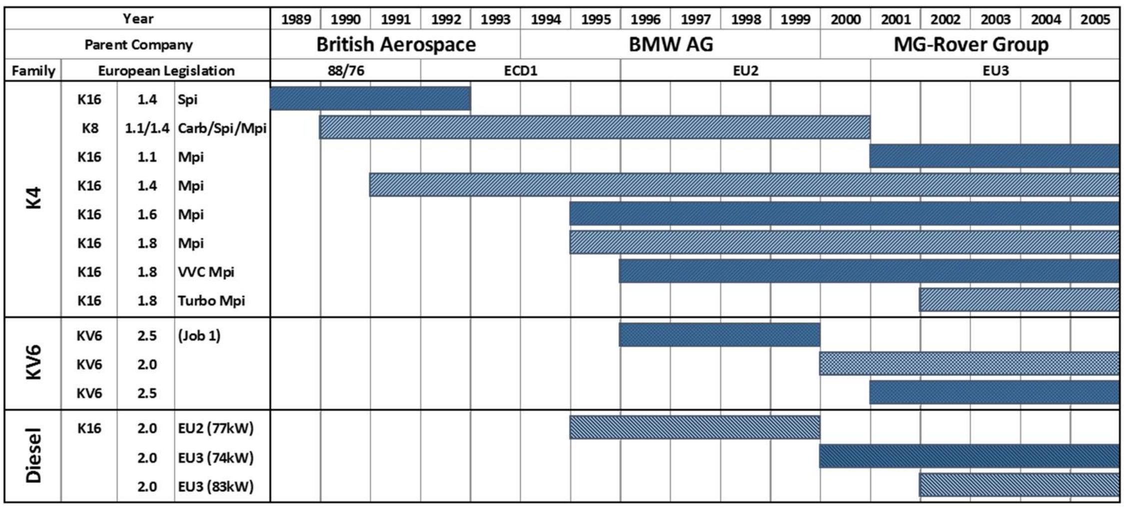

Figure 34 Rover K Series Variants.

Similar developmental and evolutionary path histories to the Rover K Series engines can be found in technical publications on other engines (Schneider & Loenigsbeck 2009, Frere 2002, Hooper 1999a,b, Eley 1963, Worters 1963, Heynes 1953). For reasons of brand management and concerns over product liability and market confidence, it is becoming much less common that companies will produce public articles and papers outlining the development history of their products, that might clearly show the limitations and constraints of their products design configurations. It was not uncommon for technical papers on engine design through the 1960's to discuss development failures and technical problems in great depth (Dawtrey 1959). This would be unthinkable in the modern era as companies seek to keep tight management of their brand and reputation. Evidence from the author's experience within the industry would confirm that the pattern of developmental issues and constraints outlined in the papers cited continues into the present. We may no longer face the circumstance outlined by S. Grylls in his 1963 paper *The History of a Dimension*, that described how Rolls-Royce were locked into the same bore centre dimension on their engines for 40 years, but dimensional constraints caused by initial equipment purchases continue to severely limit future expansion of engines in production.

2.2.5 Strategic Engine Product Planning

The costs of developing engines are very high. Table 4 shows some typical program costs for a range of engines at 1997 prices (Rankis, Simpkin & McGrath 1997). The average cost at that time was over $550M. This includes development costs as well as production tooling and equipment. Recent press articles indicate new engine program investment costs of $500M-$1B for high volume automotive plants, with upgrades to existing engine plants for new variants being in the region of $75M-$150M (Automotive World 2017, 2015, Nash 2016, Rendell 2016).

Company	Engine	Development Cost ($m)	Annual Production
GM	L850 L4	1300	800,000
Chrysler	V6 (2.7, 3.2, 3.5 litre)	625	640,000
Mercedes Benz	Modular V6/V8	1200	300,000
Mercedes Benz	C Class L4	115	Cancelled
GM Europe	Family Zero L3/L4	468	500,000
PSA	EW Petrol & DW Diesel	543	2,200,000
Fiat	FIRE L4 1.3 litre	294	365,000
Jaguar	AJ V8	305	50,000
Hyundai	DI Diesel 2.8 litre	160	200,000
	Max	1300	2,200,000
	Min	115	50,000
	Average	557	631,875
	SD	428	677,305

Table 4 Engine Program Costs. Rankis, Simpkin & McGrath 1997.

Clearly, each investment need will be unique to the particular circumstances of the project concerned. How much existing equipment is in place, what the volume requirements are for the product, what the lifecycle plan is for the plant, how much automaton is desired and a host of other factors, will all play a part in determining the level of investments required. One thing that is consistent is that the capital investment required for engine programs is always high and this will drive corporations to both want to minimise initial investment by only purchasing equipment that has a clear, defined need (no excess capacity), whilst wanting to make sure that the investments made get the best return possible by maximising production life and volumes (Page 2004, Seth 1999, Bjorkman 1995, Fine & Freund 1990). These requirements are often in conflict, but this may not be fully appreciated until after investment decisions have been made and the engine has been in production for some time, due to subsequent changes in market conditions, technologies or the competitive environment that were not known at the time of the initial investments (Gaimon & Singhal 1992).

Product Duty Cycles

Engines are designed to meet the requirements of specified duty cycles. The design calculations for load, performance, durability as well as other factors, will be driven by the particular operating conditions that are expected to be encountered by the engine over its operating lifetime. Naturally, there will be a range of operating conditions determined by the individual operational circumstances of a particular unit. The design therefore needs to consider variability in operational loads, including some additional capacity to cope with expected reasonably foreseeable deviations from normal operating conditions. Building in capacity to deal with higher loads comes at a cost of higher weight, greater package size and higher engine cost, due to larger material sections or use of higher grade materials. The engine designer therefore needs to trade-off these costs against the desire to ensure that the engine is durable and reliable in service, to protect the brand reputation of the product and meet customer expectations (Schulte & Wirth 2004).

The dominant factor in loading conditions on the engine will be the application duty cycle of the product. This is the meta-duty cycle described by its sector application. Examples of this are engines used for hand-held industrial equipment, such as leaf blowers and chainsaws, to automotive engines, through to large industrial stationary engines used for oil pipeline pumping operations or electricity generating. Each of the myriad uses of an internal combustion engine comes with its own generic duty cycle. A chainsaw used in a domestic (non-professional) application for example, might need to start reliably after long storage and only be used for 3-4 hours per year. An oil pipeline pumping engine on the other hand, might be in operation 24 hours a day, throughout the year, with limited downtime.

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Table 5 Engine Duty Cycle.

Depending upon usage profile and expected production volumes, engines may be bespoke to the duty cycle application or be drawn from a standardised engine family. At one extreme, racing engines for high performance categories such as Formula 1 are today designed specifically to meet the requirements of that application. The formula regulatory restrictions, the demands of extreme performance and the relatively open budgets to finance the design and build, mean that the costs of designing and developing an engine for this single application can be justified. In most cases however, consideration of economies of scale (see below) mean that engine manufacturers will be seeking the highest production volumes possible, to gain the greatest return of the investments they have made in engineering, plant and equipment. Even within niche applications such as Formula 1 racing, considerable efforts have been made in recent years to restrict the numbers of engines used in a season, the number of design changes allowed and the configurations adopted, all motivated by a desire to reduce the costs of the sport to participants (Federation Internationale de L'Automobile 2014).

Changes in duty cycle, such as may be imposed by a new application for an existing engine, will drive changes in the design of the product to meet altered load conditions in operation. These design changes may extend to architectural changes in the engine configuration that have a cascading impact on the machining and assembly equipment used for the engine's production. The engine's *architecture* is the layout and configuration of the principal components, such as the number and arrangement of cylinders, the valvetrain geometry arrangements, and the relative disposition and arrangement of major structural components, such as the cylinder head, cylinder block, bedplate and major cast components. The arrangement of these main components and systems play a large part in determining performance, emissions, fuel economy, weight and package size (Hoag 2006, Barnes-Moss 1973, Tresilian 1965a-i). There is therefore a competing dynamic, where manufacturers are seeking as wide a variety of applications for existing engines as possible, to extend the production life and increase production volumes, but working within the constraints of existing manufacturing equipment investments or at least minimising any plant and equipment changes that may be required.

Engine Strategies

Deciding to proceed with the design, development and manufacture of an automotive engine is a major undertaking. The costs involved in the endeavour and the commitment of resources means that it is a long-term commitment to the selected technology and configuration path. In the early days of motoring, engines were developed in isolation from a specific application. There were independent engine manufacturers, chassis manufacturers and coachwork companies that designed the external body and interior trim. A vehicle integrator, who was also usually the chassis manufacturer, would combine engines and coachwork to produce a final vehicle. Over time coachwork and engine companies were either bought out by OEM vehicle manufacturers, or the OEM developed these capabilities in-house (Langlois & Robertson 1989).

The separation of engine supply from chassis manufacture still continues in the heavy truck industry with companies such as Cummins and Detroit Diesel offering a range of standardised engines to the truck manufacturers. Whilst sourcing engines as a bought-in sub-system of the vehicle has certain advantages of reducing necessary investments and risk, it leaves the vehicle supplier vulnerable to supply issues. JCB Excavators was reliant on purchased engines from Perkins Company from the start of manufacturing of its first powered products. In 1998 the assets of Perkins were acquired by Caterpillar Corporation of USA, JCB's biggest rival in the earth move equipment industry. JCB had previously been happy to outsource engines for its construction equipment, having a relationship with Perkins that went back over 40 years. Out of necessity, to protect control of its supply, it was now imperative that JCB develop its own range of engines, the JCB444, so that it would not be exposed to this risk again. JCB therefore embarked on a program of developing the JCB444 engine family in conjunction with Ricardo consulting engineers for engine design expertise and Cosworth Manufacturing to manufacture the production units (Lewin 2005).

Companies that do not have sufficient volume to justify the large investments required for an engine program can share the risk through alliances with other manufacturers. One example of this is the PRV V6 engine jointly developed by Peugeot, Renault and Volvo in the 1970's (Gastinne, Laliere & Wallman 1976). It was used in the joint venture partners respective vehicles from 1974-1998. It was replaced by the ES/L engine also developed by Peugeot/Renault and used by them and Volvo from 1994 onward. The K9K 1461cc inline four-cylinder engine developed by Renault is currently used by Renault, Nissan and Mercedes in their automotive products. We can see from these examples that even larger automotive companies that have the technical capability and production volumes to justify their own engine production can take a pragmatic view of the need to invest in their own engine production in every case.

At the other end of the volume scale, in super luxury or performance vehicles, it may be considered necessary to have a bespoke engine for marketing reasons. Hence low volume manufacturers such as Rolls-Royce (owned by BMW), Bugatti (owned by Volkswagen) and Ferrari (owned by Fiat), all produce dedicated engines for their luxury brands that are bespoke to those application, despite limited production volumes (Rankis, Simpkin & McGrath 1997).

Economies of Scale

The linkage between unit cost and production volumes was first formalised by George Stigler in his economic paper on the topic in 1958. Stigler drew a relationship between diminishing costs with increasing production volume based on amortisation of fixed costs and efficiency gains from greater repetition in manufacturing (Stigler 1958). Increases in production allow for greater use of automation, adoption of process controls and an opportunity to absorb the investments in process efficiency improvements across the total production volume manufactured.

The early work of Stigler has been continued with applications to other industries (Hsu & Li 2009). The general pattern of costs versus volume has been found to follow an inverted power curve, with an initial rapid decline in unit cost with increases in volume, diminishing to an asymptote after a period (Celli 2013, Karsten 1997, Schmalensee 1981, Haldi & Whitcomb 1967).

Figure 35 shows a typical cost curve for annualised production of engines, based on a design study of a family of engines (Lotus Engineering 1999). Production life assumptions are 8 years. Costs fall rapidly with increased production volume but do not reach asymptotic levels until annual volumes of 100,000-150,000 units per annum are achieved.

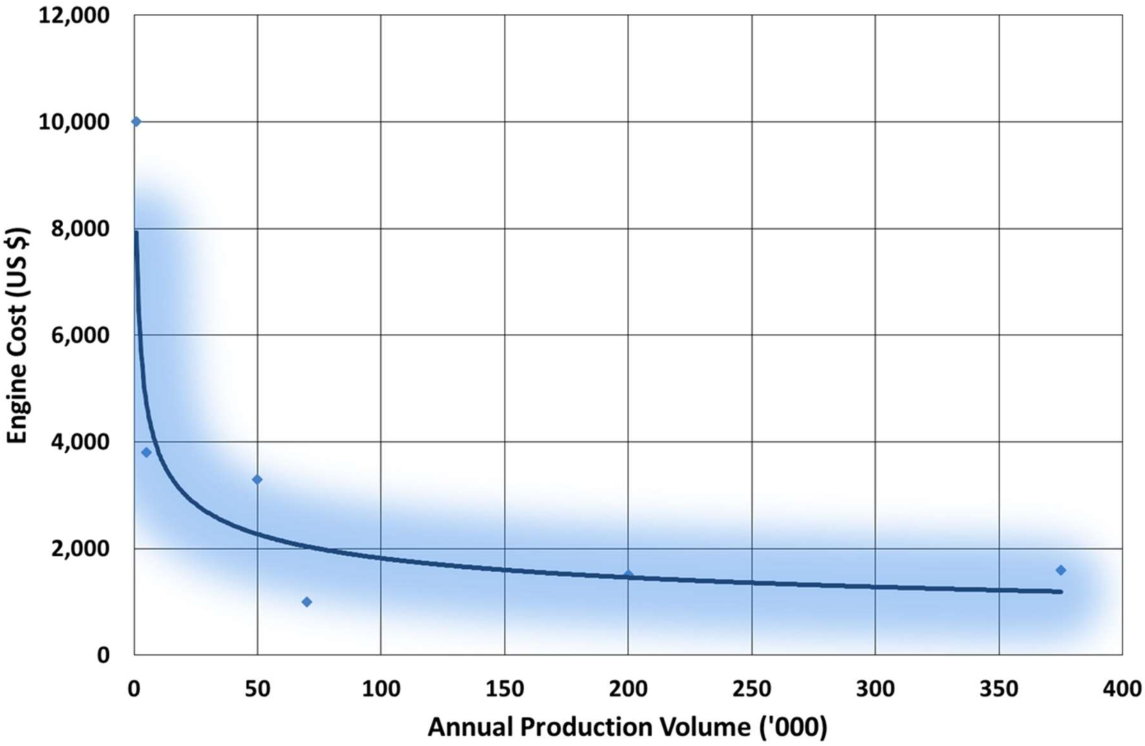

Figure 35 Engine Production Costs. Lotus Engineering 1999.

The 'knee' of the curve will be determined by factors such as the degree of automation and the level of investments made in dedicated equipment versus standard machining centres. Higher volume engines (>150,000-200,000 units/year) will benefit from dedicated transfer lines systems to reduce cycle time, reduce set-up costs and achieve higher through put rates. However, bespoke production line equipment involves high capital cost which can only be recovered across these higher production volumes, making it non-viable for annual production of <~150,000 units (Husan 1997, Fine & Freund 1990). The importance of achieving economies of scale to be a viable business has been highlighted by researchers considering the requirements of sustainable business practises (Long & Wijeyaratne 2013, Pant & Ruff 1997).

The selection of manufacturing equipment in terms of the degree of dedication of the equipment to manufacture a single design, is therefore crucially based on expected annual and total manufacturing volumes. The challenge for production planners is that these will be estimates only and there will be a need to build in flexibility to capacity variations that may be caused by a softer market for the products or other uncertainties with actual volumes required once in production (Beach, et al. 2000). This is further complicated by the design features of the engine being linked to the intended manufacturing process (Koste & Malhotra 2000). It can be seen that the engine manufacturing planners will seek to match manufacturing process selection to the production equipment based on the most economic volumes projected. Too high an installed manufacturing capacity and the investment is underutilised, resulting in a reduced cost recovery. Too low an installed manufacturing capacity and production volumes are limited, creating a lost sales opportunity for the product. Manufacturers seek to maximise production volumes to gain the most benefit from economies of scale, prompting planners to install capacity toward the optimistic end of estimates (Upton 1994).

Commonised Engines and Engine Alliances

In the automotive industry, a common way to increase economies of scale is to share engines across applications as a means of increasing unit production volume. This may mean using a common base engine in different configurations of engine so that there is an increase in total production volume of at least the base engine components, if not the whole engine. Historically engine manufacturers would seek as many opportunities where their engines could be applied as possible. The Coventry

Climax range of engines developed in the 1950s based on a small compact fire pump engine (FPE) went on to be developed for use in everything from on-road automotive applications through to outboard marine use and stationary industrial, as well as racing applications. This is not an uncommon pattern as manufacturers initially develop an engine for a primary application but then go on to further develop the engine for other uses as opportunities arise.

Specialist engine manufacturers in particular, such as Cummins, Detroit Diesel and Lister-Petter, are geared toward large variety in engine applications. Their engines are aimed at product uses that may not be able to justify the investment in the design and manufacture of a bespoke engine due to limited volumes in each application. The specialist manufacturer then has the challenge of designing a base engine range that is flexible enough to cover multiple applications, including many that will not be known when the initial design and investments are made. As this degree of flexibility requirement is known at the start of the endeavour it can be accommodated in the planning of both the product and the manufacturing equipment to produce the engine.

An example of this strategy of a flexible base engine used in multiple applications is the Cummins B series engine. These are a range of 4 & 6 cylinder engines (3.9L & 5.9L). Most commonly used in the Dodge Ram truck, this engine is also used in buses, medium duty trucks, motor homes, military vehicles, boats, generators, air compressors, mining equipment, back hoes, gravel pickers and many other pieces of construction and farm equipment. Each of these uses has a unique duty cycle that the engine design must cope with, such as constant low speed, low load duty in a pump station or variable speed, high load in mining equipment (Cruikshank & Sicilia 1997). To cope with this variety the design is robust to a broad range of load conditions. Enabling this flexibility involves a compromise to size, weight and absolute performance, as not all of the engine attributes - the features and capabilities of the engine - will be required in each application, but must be present if required. The manufacturing equipment investments must be capable of producing a range of variants of the product, with flexibility in variant volumes to match market requirements. Although costlier per engine unit to produce than a dedicated application, there is sufficient commonality to gain economic advantage across all applications due to commonality and higher volumes at a component and sub-system level.

Higher volume engine uses, such as an automotive car engine, are generally able to justify investment in a bespoke design as they have sufficient total volumes to recover the high investments required. This allows the manufacturer to optimise the design of the product to the specific use duty cycle. It also allows dedicated production equipment to be used which has higher output, lower cost and higher repeatability (Koren 2006, Koste & Malhotra 2000). This does come at the cost of limited flexibility, which can be a major constraint under conditions of uncertainty. Even in automotive applications, relatively large volumes (>150,000 units/year for 8-10 years) are required to justify this type of investment (Long & Wijeyaratne 2013).

Market data for current light duty vehicle gasoline engines gives an average production life of 8.8 years (Std. Dev. 6.27) (Autodata 2013). Multiplying this by average annual production volumes of 181,894 units (Daniels 1997) gives a typical lifetime production volume of 1,600,667 engines. The equivalent numbers for light duty automotive diesel engines are 8.5 years average production life (Std. Dev. 5.28) and an average diesel annual volume of 114,222 (Daniels 1997) gives a typical diesel lifetime engine production of 970,887 total units.

With a desire to increase production volumes, manufacturers will often consider sharing an engine design and manufacturing capacity (Daniels 1998). This may take several forms, from buying an existing engine in from another manufacturer to joint development programs with shared risk and investments to achieve the desired production volumes. An example of multiple companies using a single engine base design arrangement is the use of the JTD Multijet range of engines designed and manufactured by Fiat in Italy. As well as being used across a range of Fiat related companies, such as Alfa Romeo, Lancia, Maserati, Chrysler, Jeep and Ram Truck brands, it is also used by General Motors in their own products, as well as Suzuki Maruti and PSA Peugeot Citroen. This gives the benefits of production efficiency and bought out component purchasing power to all users of the product line.

Companies may wish to have greater input into the design features of a shared base engine and so partner to co-design a family of engines from the concept stage through to joint manufacture (Daniels 1998, Rankis, Simpkin & McGrath 1997). This enables companies to share risk and reward as it usually involves combining development resources for initial design activity and a joint venture arrangement with plant and equipment investments. One example of this approach is the Global Engine Alliance between Chrysler, Mitsubishi and Hyundai which enabled these manufacturers to share costs amortised on two million engines produced annually across five different engine plants around the world in USA, South Korea and Japan. Similar arrangements have existed between BMW/PSA, Renault/Nissan/Mercedes, Peugeot/Renault/Volvo, Subaru/Toyota and a host of other manufacturers (Suzuki 2016, 2014, Daniels 1997). In some cases, this is enabled by formal joint ownership arrangements at a corporate level, as when companies are closely aligned such as Chrysler/Mitsubishi, but on other occasions the arrangement may be established for a single engine sharing arrangement, such as between BMW and PSA on the Prince engine program used in the BMW Mini and Peugeot 208 products, amongst others. Competitive pressures succumb to the practicalities of managing cost in these arrangements (Daniels 1998).

There are other advantages to vehicle manufacturers in sharing engine platforms These include reduced cost of development and greater confidence in product launch due to proven development in an existing engine. Greater availability of common spare parts for service and familiarity with an existing engine in the dealer network, maintenance and after-market are also distinct advantages to sharing engine configurations and components.

Modular Engines

Vehicle producers often need a range of engines for their products. These may be a range of performance levels, engine displacements or even configurations. One way to handle this variety whilst minimising additional cost is to use a modular approach to engine configurations (Bonvoisin, et al. 2016, Yasushi, et al. 2008). The result is a 'family' of engines that cover a range of options with minimal parts variety (Pandremenos, et al.2009). The sharing of parts across several variants allows individual component costs to reduce due to economies of scale (Salvador, Forza, & Rungtusanatham 2002). Unique parts for each configuration are minimised and limited to 'dress' items, such as ancillaries, intake and exhaust systems. The core base engine components, the so-called 5C parts - Cylinder head, cylinder block, crankshaft, connecting rod and camshafts, are the most capital intensive and are common across the range to maximise unit volumes and gain economies of scale.

Daniels' review of the engines industry (Daniels 1997) indicated 26% of engines in automotive applications have multiple displacements from the same base engine design. These modular engines averaged two to three displacements each (average 2.6 displacement categories per engine family) with up to five displacements within the BMW L6 engine range. Other variants of engines include different valvetrain arrangements (2V/4V), pressure-charging or different performance levels from the same displacement achieved through engine tuning/electronic controls. The greatest impact of this engine variety on manufacturing equipment is in bore or stroke changes to achieve different engine displacements, followed by valvetrain variants, which affect cylinder head design. Although not without cost and complexity, pressure-charging (turbo-charging or super-charging) is more easily accommodated without significant changes to production line equipment.

Modularisation of products is an area that has been extensively explored by researchers as a means of providing variety to the end customer whilst reducing logistical complexity for the manufacturer (Bonvoisin, et al. 2016, Yasushi, et al. 2008, Salvador, Forza, & Rungtusanatham 2002). This approach is widely utilised within the engines industry, but usually requires knowledge of the expected range of variants to be produced over the lifetime of the product at the start of the concept design. By knowing all the required configurations at the point when the engine design is being laid out, both the performance trade-offs of the engine and the manufacturing set-up can be optimised. The wider the range of options to be covered in a single design, the more compromise that is required for any individual variant in terms of weight, performance, package size and other key attributes (Tresilian 1965a-i). Getting the balance right between design trade-offs at this early stage is essential if the designer wishes to specify the engine well.

Sustainability Aspects of Investment

Sustainability of resources is most often considered in terms of the lifecycles on products during their operational phases (Cooper 2010, 2005, 2000). Sustainability efforts can be approached from many angles. Although most of the work on lifecycle optimisation has concentrated on products during the use phase of their lifespan there is opportunity in examining extending the life of production equipment. Classical lifecycle cost analysis (LCCA) has looked at resources, energy and materials utilisation of the manufactured product, typically in use by an end consumer. In recent years there has been an extension of LCCA to consider whole life costs including the manufacturing and end of life disposal phases (Girardi, Gargiulo & Brambilla 2015), extending this as far as 'ore-to-ore' analysis looking at manufacturing from minerals extraction through end of life disposal back to base materials (Tatemichi & Yoshida 2001).

These analyses can uncover a very different perspective on the costs to society and the environment through the adoption of new technologies. Internal combustion engines carbon emissions and environmental impact has traditionally been dominated by the usage phase of operation. With the emergence of wider adoption of electric and hybrid vehicles LCCA research has shown a shift in emissions and carbon production from usage, more to manufacturing and disposal phases for these types of vehicles, although these still currently remain relatively small compared to the usage phase. One of the challenges with LCCA analysis is that there are no standardised or consistent models for performing the analysis. A wide variety of inputs are used, leading to analysis that has internal consistency (comparative analysis within the same study), but little absolute relevance. Comparing LCCA analysis between studies is therefore almost impossible.

Consumers are becoming much more conversant with the idea of energy and resource efficiency in the products that they purchase. This is partially driven by labelling schemes and also a greater awareness of the benefits to the environment of making more sustainable choices. The increase in recycling rates is a reflection of consumers becoming more aware of the impact of end-of-life disposal to the environment. Beyond recycling, there is a growing interest in up-cycling, refurbishment, re-purposing and re-use of products.

Manufacturing tooling and equipment is part of a wider ecosystem supporting the product through its life (Nieuwenhuis 2014). The equipment used in the production of components and systems for engines can itself be thought of as a product that needs to be manufactured, has a useful life and is then disposed of by the manufacturer. Relatively little research or analysis has been done on understanding the lifecycle of plant and equipment used in manufacturing or in extending the life of the manufacturing product during its usage phase (Fine & Freund 1990). Since the beginnings of the automotive industry there has been a second life market for automotive production equipment. European and US automotive manufacturers would often resell complete engine transfer line systems to other manufacturers in developing countries at the end of their product life for the original equipment manufacturer. Examples include Fiat selling production lines to VAZ/Lada in Russia and Chrysler to FAW in China (Kolomytsev & Gusev, 2011, Weertmann 2007). The second use purchaser might buy a license to produce the complete engine, which was usually limited to their own domestic sales. This would require them to not only buy all tooling and equipment necessary to manufacture the engine, but also the relevant know-how and production process information. The purchase was usually for the 5C parts, with all other components continuing to be supplied from a tier 1 network of suppliers. The fact that there was sufficient life in the engine production equipment to make it worth the second user shipping and installing the used equipment in their plant, is an indication of how much life typically remains in automotive production manufacturing equipment.

Individual machines and process equipment can also be re-purposed into a second life, making alternative products and not limited to producing the same products for which they were originally manufactured. Flexible equipment allows for retooling to produce a wide variety of parts and provides greater opportunity for resale and extended life. Equipment more dedicated to producing a specific design of component, such as transfer lines, are custom built not only to make one product but often only one set of dimensions. The cost of changing to produce different products can be prohibitive (Pant & Ruff 1997, Jung & Colgan 1995).

Given the large investments made into production line equipment (Automotive World 2017, 2015), extending their life will give large benefits in providing a greater return on investment. Gaining more useful life from the equipment allows deferral or even elimination of investments in new equipment for later engine variants or replacement product. This reduces the demand for resources and materials with consequential benefits to the environment and society. In this way, extending production equipment life has an immediate and significant positive impact on sustainability objectives.

The continued production of related products, albeit possibly with minor changes to geometry, will enable the continued viability of any supporting industrial ecology (Kimure & Nielsen 2005). For each engine design configuration that is produced there are related supplied components with their own associated tooling and equipment. There will also be an industrial ecology of other supporting aspects, such as maintenance, repair and service, associated with the engines produced. When an engine goes out of production this ecology either needs to be re-purposed or is made obsolete. Extending the production life of the 5C components allows the extension of the supporting ecology for those 5C parts, multiplying up the beneficial life extension considerably (Nieuwenhuis & Lammgard 2013).

Satisficing in Engine Design

The idea of 'satisficing' was introduced by Herbert Simon in his book *Administrative Behaviour* in 1959. In discussing the administration of business operations, Simon notes *"Whereas economic man supposedly maximises - selects the best alternative from among all those available to him - his cousin, the administrator, satisfices - looks for a course of action that is satisfactory or 'good enough',"* (Simon 1997 p.119). Replacing 'economic man' with engineer and 'administrator' with designer, and you have a fair representation of the difference in approach to engine design applied by the engines concept designer versus an approach of functional optimisation that might be adopted by the engineer. The engineer is trained to always optimise, whilst the concept designer's has a broader perspective and is focused on compromise and trade-offs.

Engine manufacturers and product planners can unconsciously adopt a satisficing approach to engine strategies. A conservative approach to planning designs and manufacturing minimises technical and market risks. This is particularly important given the large capital investments required for engine production (Automotive World 2017, 2015, Rankis, Simpkin, McGrath 1997). If a current design configuration has proven satisfactory in the past, the replacement engine will develop from a similar concept rather than incorporating any radical new changes. There are several advantages to this evolutionary approach; it maximises the carryover of existing knowledge and experience of the engine technologies and it reduces risks of unknowns not only in the engineering community but also in manufacturing, sales and field support.

Existing infrastructure is more likely to continue to be useful in supporting the new engine if it has some commonality to a previous product. Given the large number of factors that a new engine design must cater for from performance and legislative requirements, to unit cost considerations, vehicle packaging and field support and maintenance, the diligent engine designer has a complex task in getting the right compromises in engine configuration. This naturally leads to satisficing designs rather than optimising them.

2.2.6 Concept Design Processes in Engine Design

The concept design of an IC engine begins with establishing the functional requirements for the finished product and any constraints, whether technological, geometric, economic or logistical, that will affect the final design (Hoag 2009, Heywood 1998, Tresilian 1965a-i). A useful framework for establishing the basic process of engine configuration is provided by Dopson, Taitt & Sandford (1995). This paper discusses the sequence of approaching the iterative selection of suitable engine geometry through analysis, to meet functional targets through a process of selecting initial geometry and evaluating achievement of target objectives through calculation and simulation.

The concept design process of engines starts with laying out base engine dimensions, sometimes referred to as the *scantlings*, a term borrowed from ship building. The basic dimensions that determine the overall layout (the architectural arrangement and disposition of the major components and their geometry), the configuration (the specification of key systems and components) and package size of an engine are relatively few in number. The bore and stroke of the engine together with the cylinder count, determine the engines displacement (Manning 2012). The bore/stroke ratio (B/S) affects function, with a long stroke engine (B/S <0.9) producing less side force on the cylinder, lower friction, greater torque and better fuel consumption. The package of a long stroke engine is relatively tall and less space efficient, with a higher centre of gravity. A shorter stroke engine (B/S >1.2) provides more space in the combustion chamber for valve area (larger valves), hence providing a better breathing engine which results in higher performance. A short stroke engine has the additional advantage of lower reciprocating mass in the piston and connecting rod, allowing for a higher maximum engine speed - Mean piston speed over the stroke of the engine is used as a metric for engine reliability. This also translates into an increase in engine power output. Race engines are typically short stroke to take advantage of their performance benefits. The larger diameter to bore to stroke ratio in short stroke engines creates challenges in maintaining bore sealing due to cylinder distortion. The greater ratio of crevice volume around the piston rings combined with poorer sealing on these engines means that they have poorer emission performance compared to a longer stroke engine of the same displacement. Automotive engines tend to be *square*, that is have a B/S ~0.9-1.2, to balance emissions, thermal efficiency of combustion (better combustion wall surface to volume ratio) and power performance (Roberts & Collins 1976). This arrangement also results in a fairly compact package size. Figure 36 shows the relationship between bore/stroke and performance (Hoag 2006).

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Figure 36 Bore/Stroke Effects. Hoag 2006.

Once an appropriate bore/stroke ratio is established, clearance requirements between the bottom of the piston at Bottom Dead Centre (BDC) and the crankshaft balance counterweights, will determine the connecting rod length. Figure 37 shows clearance requirements for piston and crank over the stroke of the engine cycle, which defines the cylinder block height. Adequate clearances between rotating and reciprocating components must be provided under static and dynamic loads. However, the engine designer will seek to minimise package size to reduce weight and cost, and make installation of the engine easier.

Figure 37 Cylinder Block Height Determination. Hoag 2006.

The connecting rod length and the crankshaft throw will determine the bottom end size and shape. The crank throw describes a connecting rod excursion envelope which must be cleared by the cylinder block. It can be seen that this dimension directly relates to the engine stroke and the connecting rod length.

Figure 38 Connecting Rod Throw. van Basshuysen & Schafer 2004.

Figure 39 shows how bore/stroke considerations in a vee configuration engine influence package size due to the requirements for piston clearance at Bottom Dead Centre. Vee angles are usually determined by engine dynamic balance requirements (Hoag 2006, Heywood 1988, Frass 1948), resulting in the typical 90-degree vee for two-cylinder V2 engines, 60-degree vee for six cylinder V6 engines and 60/90 degree vee for eight cylinder V8 engines. Race applications will occasionally compromise achieving primary and secondary balance, to take advantage of the lower centre of gravity and the reduced aerodynamic profile of very broad vee angles e.g. 111-degree V10 Renault F1 engines of 2001, rather than the 72-degree vee that would be required for best engine balance of primary and secondary forces.

Figure 39 Piston Clearance Considerations. Hoag 2006.

Together with the number of cylinders and the arrangement chosen (vee, in-line, boxer, radial, opposed) the overall package size of the engine will be determined by the values selected for these key dimensions. It can be seen that bore, stroke and numbers of cylinders establish a proportional profile for the cylinder geometry. The vee angle chosen will impact the installation package shape and size. Figure 40 shows a comparison of engine profiles for three vee engines of the same bore/stroke ratio, all of four cylinders and 1.2 litre displacement. For comparison, these are overlaid on a profile of an inline engine four-cylinder arrangement. Note how alternative choices in engine geometry have had significant effects on engine size and arrangement.

Figure 40 1.2 Litre L4 Layouts. Barnes-Moss 1973.

Thus, a few core dimensions of bore, stroke, and rod length, together with number of cylinders and their arrangement, will set out the basic size and properties of the engine. The choice of these few key dimensions and their architectural arrangement will be a combination of package considerations for size and shape, performance levels sought, emissions and fuel economy requirements, thermal management, noise and vibration characteristics and a host of other objectives for the engine.

These key dimensions form the starting point for more detailed design of the engine architecture, incorporating aspects such as the structural requirements of the powertrain and layout of cooling passages and oil systems. Figure 41 shows how the arrangement of cylinder head bolts is a trade-off between good gasket sealing, structural integrity requirements of the major casting and allowing the passage of oil and coolant around the engine. A close arrangement of the cylinder head bolts to the cylinder bore will improve head gasket clamping and reduce package size and weight However, this is traded-off against a constraint being placed on future geometric expansion of the engine if the is a need to increase cylinder bore size at a later date.

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Figure 41 Head Bolt Layout. Manning 2012.

At the earliest stages of concept design, no analysis will have been yet conducted. In order to perform even provisional analysis and design calculation the base scantlings must first be determined. To assist with configuration of the engine, concept designers use information on successful designs from benchmark data in combination with their own expert knowledge. Engine designs are parametric in nature, with each key dimensional change having a cascading knock-on effect to related dimensions of other components due to the tight arrangement of features. A proportional approach to the design of engines was laid out by Stuart Tresilian in a series of articles in the *Automotive Design Engineering* publication (Fenton 1986, Tresilian 1965a-i). This approach was expanded by Barnes-Moss in 1973. These publications neatly summarise the parametric approach taken by most designers in initial concept design and are seminal texts in engine concept design practice. Figure 42 shows an example from Barnes-Moss of how benchmark data can be used to establish relationships between parameters and anchor the design in feasible regions of the design space (Barnes-Moss 1973) - see also section 3.6 Design Space Modelling.

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Figure 42 Engine Friction Benchmarking. Barnes-Moss 1973.

A series of proportional parameters can be used to define features of the engine, based on a ratio system, with the bore dimension as the key parameter. Figure 43 shows cylinder block arrangement (bore centres), for cylinder blocks with different cylinder cooling options, as a ratio of bore size. The proportionality of the designs illustrates how a change to one dimension (bore) can have significant effects on the geometry of the whole engine.

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Figure 43 Cylinder Block Parameter Design. Barnes-Moss 1973.

The bore does not just determine dimensions directly related to the cylinder block. The effect of bore selection also impacts other key dimensions such as those of the crankshaft and piston, as can the principal dimensions of the inlet ports, valvetrain geometry and the gas path through the engine. Figure 44 illustrates the proportional design starting point for crankshaft and piston geometry, where the key dimension ‘D’ is the bore diameter. These components will be further refined through detail analysis at a later stage of the engine development process, but at the concept stage, parametric design allows feasible geometry to be quickly established.

Figure 44 Crank & Piston Parametric Design. Barnes-Moss 1973.

Beyond the design of structural components, parametric design based on key dimensions can also be used for gas path and aerodynamic features of the engine, such as the intake and exhaust port geometry in the cylinder head. Figure 45 shows the layout of intake port and valve geometry, which will be crucial in engine breathing and performance, based on ratios of engine bore diameter ‘D’. As with other geometry, final geometric definition and dimensions will result from detail design and analysis using techniques such as computational fluid dynamics analysis (CFD) and validated through testing. However, these more sophisticated techniques require feasible starting geometry. It is parametric proportional design, validated through benchmarking data, that allows heuristics to be established and the concept design to proceed.

Figure 45 Port Parametric Design. Barnes-Moss 1973.

Once proportional design has established the overall configuration of the engine, options can be considered for modifying the arrangement to suit specific trade-offs. Figure 46 shows the effect of changing bore/stroke for a longer stroke for improved fuel economy. This results in a larger package size for the engine (Mackerle 1972). The final choice of arrangement is a multi-criteria optimisation problem. With incomplete information at early stages of the concept design process, the designer must make some initial choices of key dimension values. These are based on prior experience and benchmark data, using heuristics or *rules of thumb* on feasible values.

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Figure 46 Bore/Stroke Package Impacts. Mackerle 1972.

It is only once the key configuration has been established by this heuristic parametric process that further analysis and optimisation of systems and components can occur. It is at this point that the architecture of the engine tends to get fixed, leaving little opportunity for base key dimension changes afterwards. Interviews with engines concept designer (see section 3.3) reveals that key engine geometry evolves away from the initial geometry only as much as needed to achieve target objectives after initial setup. In other words, more radical geometry and layout is usually only considered at the preliminary concept stage, when relatively little analysis has been completed. This means that the designer makes these decisions based almost entirely on heuristics derived from existing knowledge and benchmark information.

As can be seen from the use of parametric modelling a change of one dimension, even to a relatively small degree, can have a significant cascading effect throughout the engine. Not only does this alter the size and arrangement of the engine, but it would mean all of the detail modelling and optimisation would have to be run again at great cost and loss of engineering time. There is therefore a disincentive to change the base dimensions once established even at a stage before anything has been committed to hardware and investments in tooling have been made. As the design activity progresses this pressure to lock into key dimensions such as bore/stroke becomes all the greater.

Use of Heuristics in Engine Design

Heuristics are 'rules of thumb' developed from experience (Gigerenzer, Hertwig & Pachur 2011). Heuristics provide a basis for future decision making built on known data points from prior experience of similar circumstances. They are a mechanism for evaluating risk in future options using limited information. Closely related to the concepts of Bayesian modelling of priors (use of prior information on attribute values to predict future values), heuristics embody psychological approaches to the interpretation of limited data and its application to informed decision making. Studies of the use of heuristics incorporate aspects of behavioural sciences and are not just viewed from the narrowly numerically deterministic stance that is often adopted by Bayesian or other forms of probabilistic modelling. Known solutions from prior cases are generalised and used as guidance for filling in missing data for the current situation.

Heuristics have proven useful in a number of subject areas including economics, social ecology, politics and negotiation (Kahneman, Slovic & Tversky 1982). They provide us with guiding rules under conditions of uncertainty, allowing us to be able to progress with processes and actions using stochastic techniques. This is usually anathema in the field of engineering as data driven decision making is the aspiration, if not the norm. Like most real-world endeavours, there is probably a greater degree of uncertainty than we would like to admit. In these circumstances, acknowledging the unknown or uncertain elements and bolstering decision making with a structured process of evaluation can help us to progress with more confidence (Gigerenzer 2008).

Design is fundamentally a process of crafting solutions under conditions of incomplete information. In this endeavour, heuristics help guide the designer to the area of feasible solutions in design space - See section 3.6 Design Space Modelling. A heuristic is a rule of thumb that allows for decision making, when a complete set of facts is not available and therefore applies well to the early stages of a concept design process (Lee & El-Sharkawi 2008).

In product design heuristic rules may be formally codified in design standards, design principles or informally applied by the design through the use of past experience about what does and does not work in design - the designer's intuitive knowledge (Persson 2012, Yilmaz 2010). When knowledge of direct experience of prior design work is lacking it can be inferred by benchmarking examples of similar designs. Benchmarking competitor designs has a long history. Formal techniques for assessing adversaries' technical and equipment capability were perhaps first developed into a structured form during WWII by both the Allies and the Axis powers. The Air Intelligence Unit in the UK had teams of pilots, engineers and analysts whose role was to recover captured aircraft and evaluate their capability, probing for areas of weakness that could be exploited and seeking opportunity to copy novel solutions (Bingham 1998). This approach was also adopted by the German air forces and other Axis and Allied powers as a means of developing defensive strategies, but also as a means of improving their own designs (Smith, Creek & Petrick 2003, Stapfer 1988).

An illustration of the importance of this form of competitor benchmarking during this period was the case of three United States B-29 bombers on a raid over Japan that were forced to land in Russian due to shortage of fuel (Gordon & Rigmant 2002). Although the Russian and American forces were allies Russia was reluctant to return the bombers as they contained technology of great interest to the Russian air force. One of the aircraft was used for flight trials, whilst another was stripped down to individual components so that they could be measured, weighed and reverse engineered. This established a pattern for benchmarking activities that has persisted to today, where three copies of a competitor product might be obtained - one for complete product evaluation, one for tear-down analysis and one for limit testing to destruction to find key vulnerabilities.

The tear-down components were displayed in an 'exhibition' at the Tupolev design bureau for engineers and suppliers to be able to familiarise themselves with the design (Figure 47). This was part of an objective to reverse engineer the complete bomber for manufacture in Russia. This was eventually done and the bomber was designated the Tupolev TU-4.

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Figure 47 TU-4 Exhibition. Gordon & Rigmant 2002.

The skills and processes developed by technical units in WWII went on to be used by industry after the war. A British government sponsored project conducted a technical evaluation of the Mercedes Silver Arrows race cars (1934-1939 era) using many of the techniques developed by the Air Intelligence Service during the war (Earl 1947). This type of process became the blueprint for obtaining benchmark data. Figure 48 shows an example of the use of benchmark data for evaluation of competitor product on engine designs in the automotive sector today (Adachi, et al. 1998). In this case, the mass of a range of competitor inline four cylinder naturally aspirated engines is mapped against engine displacement. The data is categorised into engines with cast iron cylinder blocks and aluminium cylinder blocks, to look for patterns in the design feature under consideration (block material) against a key parameter (engine mass). The competitor data used will be obtained from published materials or from direct measurements from sample units purchased for the purpose of benchmarking. The new design being proposed by the authors is shown in relationship to the competition (engine designation 1ZZ-FE). This indicates its relative low mass compared to the competition.

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Figure 48 Cylinder Block Benchmark Data. Adachi, Horio, Nalamura, Nakano & Tanke 1998.

Benchmarking data points are very useful in helping concept designers target specific regions of a design space as they show known feasible solutions and also identify whether there may be direct competition at a particular design point. Figure 49 shows the type of base engine data regularly published in engine technical papers. Even with such sparse data, it is possible to extrapolate useful information using parametric design methods using the heuristic techniques described above (Doi, et al. 1994). The essential data of bore, stroke, configuration and package size are presented, allowing the engines concept designer to build an accurate picture of the design architecture for concept comparative purposes.

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Figure 49 Engine Technical Data. Doi, Kimura, Murata & Ohki 1994.

More detailed analysis of benchmark data from measured engines purchased for the purpose, can be used to establish core engine dimensions (Ecker, Schwaderlapp & Gill 2000). Figure 50 shows relational information on bore-to-bore distance on engines across a range of engine displacements. There will be variation due to particular circumstances and decisions on acceptable design risk taken by each engine designer, but a generalised trend relationship can be seen. It is this generalised parametric relation (design heuristic) that is of use to the engine concept designer in exploring feasible geometry options at the earliest stages of the design process (Cantore & Mattarelli 2004b).

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Figure 50 Benchmark Data. Ecker, Schwaderlapp & Gill 2000.

2.2.7 Potential for Biological Analogy

The evolutionary development of engines over their lifetime and the requirement to satisfice multiple criteria in dynamic environments is analogous to natural evolutionary processes. Nature can be considered an optimisation engine, continually testing resource expenditures for efficiency and fitness to conditions (Flatt & Heyland 2011, Jones 1995, Martin 1995). Biological models have potential to bring a broader perspective to design space trade-offs than a simple focus on functional optimisation. The next sections of this thesis will look at biological theory related to form, fitness and the success of morphological geometry and how this might act as a guide to design configuration choices.

2.3 The Application of Biological Models

Biological models, whether through analogy to evolutionary processes, mimicry of bio-inspired design features or direct modelling of natural systems processes such as the development of genetic algorithms for optimisation, allow human systems to take advantage of the living world as a library of knowledge resources that can be applied to aid human endeavours.

In particular, Darwinian evolutionary models have been applied to an array of topics from the fields of social sciences, engineering, politics and business, to the worlds of finance and banking. Natural systems have developed to be efficient in operation and robust to change - attributes that are also required in many of the processes and systems in society and the human structured world. Just a few of the many areas of application of biological models are:

- **Economics** - Behavioural economics systems based on ecological networks and models of predator/prey interactions.
- **Business** - Ecologies of interrelated energy networks, co-dependent for system survival.
- **Social ecology** - Interactions of social systems as mirrors of natural ecologies.
- **Industrial ecology** - The systemic analysis of industry as an ecosystem and its impact on the environment.
- **Engineering** - Optimisation of designs using genetic algorithms to develop the fittest features through multiple generations.
- **Materials** - Bio-mimicry of materials properties to solve intractable problems.

Biologically inspired concepts are not limited to specific disciplines, but can be used in the study and optimisation of generic processes in engineering and manufacturing. These can be applied to a wide range of problem areas including:

- **Decision making** - Optimal trade-offs between options utilising fitness values and resource optimisation.
- **Evolutionary/change processes** - Resilience to changing environments and fitness for the operating environment.
- **Value attribution** - Satisficing in multi-criteria decision trade-offs.

Specific techniques that have been developed to enable the application of biological models can be illustrated by the development of genetic algorithms in computer modelling and simulation that are now widely adopted as an option search method. Figure 51 illustrates this approach with the example of a crane jib design. The traditional structural analysis of a crane jib to carry a fixed load might result in a satisfactory but sub-optimal solution. The mass of the jib arm in this example is 922kg. It follows a form that might intuitively be sketched out by a structural engineer, imagining load paths on the jib and resolving those loads by the careful placement of compression and tension elements in the jib arm design. Optimising around this design by the use of classical engineering calculation might iterate to a local optimum point using traditional 'hill-climbing' optimisation processes. These techniques apply a fitness value to an imaginary landscape of attributes of the design under consideration - x_1 and x_2 in Figure 51. Selected values for x_1 & x_2 will place a design at a corresponding point on the design landscape. This point will have a fitness value that can be assessed against nearby points on the same landscape terrain. If a higher fitness value is adjacent to the current point, the next iteration of the design moves to that location. Over many iterations, the preferred design point moves to ever higher fitness values until it achieves a peak value. In this way, it *climbs* the hill of fitness to find the peak.

Algorithms based on genetic models are able to take advantage of modern computing power to find alternative solutions by examining thousands of different design permutations in a short time. This is achieved by coding key design features, usually geometry, as a form of 'DNA'. Each design DNA combination will have certain fitness against achieving desired design attributes such as mass, size, strength, etc. A computer program can iterate through many generations of design, recombining the fittest features and design arrangements to find an optimal solution (Holland 1995). For each iteration of design, successful design features, as determined by success criteria programmed into the code, are carried forward to a next generation design arrangement. Less successful features are gradually eliminated. This process is in essence no different from the process of gradual evolution that a designer might intuitively perform, albeit in this case with many more generations of design due to the fast processing power of the computer. What makes the genetic algorithm different is its replication of the mutation function within nature. Random changes are introduced to the DNA code for the design, much as might occur naturally in nature to a biological entity that evolves over many generations. Some of these mutations will be detrimental and soon be selected out. Others, however, will make 'leaps' to nearby peaks of fitness that might not otherwise have been encountered (peak 'A' Figure 51).

This provides a distinct advantage over traditional hill-climbing techniques which get stuck on local optima and cannot move to global optimum. The designs thus produced are often counter intuitive to a conventional design approach. In the example of the crane jib, as design at peak 'A' carries the same load as the original optimised conventional design (peak 'B') but requires a much lower jib arm weight (718kg). This results in less material use and better operational function (crane dynamics and response to wind speed).

Figure 51 Application of Genetic Algorithms. Adapted from Holland 1995.

It can be seen from these examples that the use of biological models and evolutionary development theory can be a rich field for analogous application to mechanical design and product development, aiding geometry optimization.

2.3.1 Evolutionary Theory in Biology

The formalisation of the theory of evolution was set out by Charles Darwin in his seminal text, *The Origin of Species*, in 1859. Starting from his observations during the scientific voyage of *The Beagle* which circumnavigated the globe (1831-1836), Darwin refined his theory of the transmutation of species by careful study and experimentation over the next 20 years. Prompted by correspondence with Alfred Russell Wallace (1858) which indicated that Wallace's own work on species development through an evolutionary mechanism was ready for publication, Darwin finally submitted his own treatise on the topic for publication (Darwin 1859). The concept of evolutionary development in plants and animals was further developed by Darwin over six of editions of The Origin of Species during the next 18 years.

Darwinian evolution has become the predominant model for explaining the development of life on earth. The principle characteristic of this mechanism is 'decent with modification'. The offspring of a biological entity will be subject to modification due to random mutation of genes. This process is undirected and the success or failure of a mutation is subject to the vagaries of the environmental pressures that come to bear on the individual. In this context, 'success' means the ability of the biological entity to survive and reproduce. Although the battle for survival occurs at an individual level, it is the preponderance of genetic makeup of the *population* which determines the overall success of a species.

There is no single, agreed definition of what constitutes a 'species'. The Oxford English Dictionary defines species as *"A group of living organisms consisting of similar individuals capable of exchanging genes or interbreeding"*. This definition outlines the importance of relatedness between individuals and the need to be able to draw relationships from parent to offspring through direct lines of reproduction.

Biological entities are subjected to a host of environmental pressures. These include elemental pressures of temperature, humidity, variable weather, etc., predation pressures, the need to constantly acquire sources of nutrition and competition for reproductive mates. Any advantage an individual may have in dealing with these challenges will increase the probability of survival and the likelihood of reproduction, thus passing on favourable genetic makeup to succeeding generations.

In engine design, a family of related engine variants might be considered as a 'species' of the product - An evolutionary line of decent building on the successful design attributes of prior generations of the product and able to combine features to create a next generation of product that has higher fitness to better match a new set of environmental conditions. An ‘individual’ in this context is therefore a single engine unit, with its distinct lifecycle. This thesis is concerned with the development of engine species, rather than the lifecycle of individual units, as this determines design configurations.

Darwinian evolution postulates three factors in decent with modification:

1. Variation - A population is extant that has variety in its genetic makeup. This provides a range of characteristics that can be ‘tested’ by the environment. If all entities are equally adept there is no advantage to selection pressure. The greater the variety in a population the more robust it is to a range of environmental conditions.

In engine design *variation* is achieved through different configurations and features of engine designs - their specifications. Quality systems and processes seek to minimise variation of dimensions or other deviations between individual engine units, to ensure reliability and good function. However, a single engine family may have several variants with distinct features, such as a range of displacements, different valvetrain arrangements (single/double cam, 2V/4V), pressure-charged or naturally aspirated options, etc. This variation of designs can be tested in the market for fitness against the environmental conditions and competing products. The fittest configurations will have a higher probability to be reproduced in subsequent generations of the product design. Variants that prove less fit for purpose will be less likely to be reproduced in succeeding generations of the product.

2. Selection - The relative success or failure of an individual in a particular environment will be the result of how well matched the characteristic attributes of that biological entity are to their environmental conditions. Those entities that have more favourable characteristics will be more likely to survive and reproduce. Over an entire population the dominant characteristics will evolve to define a species.

The selection pressures on engine designs come from the drivers for change - see section 2.2.3. These include market forces, competitor products, regulatory and legislative requirements, social pressures, economic factors and customer performance expectations. Those product designs that prove to be the best fit to match the needs of these market requirements will be commercially successful and selected to be reproduced in subsequent generations of product. This may be in continued manufacture of a design that satisfices current and future requirements, or in the selection of particular design attributes to be carried forward into a next generation design.

3. Inheritance - The characteristics that enabled successful survival must be capable of being inherited by subsequent generations. The science of genetics was unknown to Darwin, being first postulated by Gregor Mendel from his work on selective breeding of pea plants between 1856-1865, and remained obscure until the early 20th century. However, a principal characteristic of Darwinian evolutionary theory is inheritance through genetic mutation.

Successful engine design configurations or features will be selected to be carried forward into the design of next generation products. Designs follow an evolutionary path, building on prior successful designs (Ehlhardt 2016, Eger 2013). In this way design attributes with the greatest fitness to achieve requirements are incorporated (inherited) by subsequent designs.

Evolutionary Theory and Ecology

The natural or Darwinian evolutionary process is an outcome of decent with selection. It is the path that something has taken through a series of changes where, from a population of variants, some have proven to be more able to survive in a given environment than others and have gone on to reproduce and pass on their unique genetic code to a next generation. In nature, this process is enhanced by random mutations that occur, providing a capability to make genetic ‘leaps’ to overcome getting trapped at local optima fitness peaks. In this context evolution in undirected - it has no ‘purpose’ or final goal. The evolutionary path is therefore not a predictor of the future, but merely a reflection of the past matches of entities to the environments in which they found themselves.

Figure 52 shows an image of two members of the shrew family and two from the hedgehog family (Dawkins 1996). Hedgehogs and shrews have followed distinct evolutionary paths to become separate species. Both of these species have continued to evolve to adapt to their local environments in order to survive. This has resulted in form adaptation that converges to body plans that mimic that of the other species. This sounds like a deterministic approach involving choice and intent i.e. the individual animals *adopted* the body plan attributes favourable to their survival. In reality, the members of the particular hedgehog or shrew family that survived and went on to replicate are the ones that had the best set of attributes (by chance) for survival in their local environment at the time. In Figure 52, the two hedgehogs are shown at the top of the image. The Algerian hedgehog Erinaceus algirus (a) and its close cousin, Neotetracus sinensis (b). The two animals shown at the bottom of the image are members of the shrew family, Setifer setosus (c) and the long-tailed tenrec, Microgale melanorrhachis (d).

Figure 52 Hedgehogs and Shrews. Dawkins 1996.

This image illustrates how the environment favours particular body shapes and attributes such as fur cover, defensive spines, body size, feeding behaviours as well as other factors. The typical body plan that we associate with ‘shrew’ or ‘hedgehog’ is therefore as much a reflection of a match to local environmental conditions, its fitness, as it is a representation to any given species body plan.

On a functional level biological entities and human made products are subject to the same constraints of physics and chemistry. The limitations of materials, structural mechanics, thermal properties and other aspects of the physical world, determine viable form and functional performance (McGee 2007).

Figure 53 shows the insulation properties of fur for a number of animals that need to survive across a wide range of environments.

Figure 53 Thermal Insulation of Animal Fur. Schmidt-Nielsen 1979

Figure 54 shows the heat transfer characteristic for cooling fins on an air-cooled engine design. This is inversely analogous to the insulation properties shown in Figure 53. In both cases the heat transfer properties are defined by the material properties and physical form e.g. section size or length. The thermal performance is therefore a function of the 'design'.

Figure 54 Thermal Performance of Cooling Fins in an Air-cooled Engine. Mackerle 1972.

This relationship between biological 'design' form and the needs of artificial products gives us an insight into how we might learn from the optimisation processes for survival that have made certain forms in nature successful over millennia. Biological forms have evolved to be successful in satisficing multi-criteria to achieve survival in challenging environments, whilst minimising resource consumption and waste. Working within the constraints of the same laws of physics, human engineered products must also satisfice a range of complex and conflicting criteria in a resource efficient manner analogous to the challenges biological entities face in nature. Human designers can therefore learn from nature in optimal methods of achieving these objectives through analogy (genetic algorithms), mimicry (bio-mimicry) or process (evolutionary design methods) (Martin 1995).

Darwinian and Lamarckian Evolution

The primary difference between biological evolutionary paths and those of artificial artefacts is that the designer can provide intent in the direction of travel, whereas natural evolution is undirected and is a consequence of fitness to prevailing conditions.

Darwinian evolution is based on the undirected random mutation of genes. The desires and behaviours of the individual, in so far as they influence inheritance, play no part in the probability of the survival of the species. The chances of any particular genetic code being passed on to subsequent generations is a question of the best match to current conditions between the extant population and the prevailing selection pressures.

The evolution of human engineered and manufactured products therefore more closely matches a Lamarckian model of evolution rather than a Darwinian model. The theory of evolution proposed by Jean-Baptiste Lamarck in his *Theory of Inheritance of Acquired Characteristics* (1801), proposes that an organism can pass on characteristics that it acquires through its behaviours during its lifetime to its offspring. Lamarckian evolutionary theory therefore allows for intention and directed evolutionary traits.

The possibility of intentionality on selection marks out Lamarckian evolution as a better fit to modelling human influenced choices in determining the breeding of plants and animals or as applied to design choices in product evolution. Evolutionary models, whether of the Darwinian or Lamarckian variety, have proven useful to analysts of trends and their development over time in a number of areas beyond the biological world including finance, social sciences and engineering. In any event, the process of selection of form to match the environment i.e. fitness, is the same in both Darwinian and Lamarckian schools of though.

2.3.2 Phenotypic Expression

The coded information for the building of life forms is transmitted in DNA (deooxyribonucleic acid). This code provides the instructions for the form, growth and development, function and reproduction of organisms. The physical expression of the genetic code in a biological entity is called the phenotype (Piersma & van Gils 2011). This is the observable characteristics of the plant or animal including its morphology and behaviours. The layout of the principal morphology of animals is known as their 'body plan'. This is the arrangement of key body parts, their relationship, size and configuration. The body plan forms one of the key mechanisms for biologists to characterise different species of plants and animals as morphology plays such a large role in the relationship of the organism to its environment. The fitness of the body plan to the environment in turn influences the likelihood of success in survival and reproduction.

The corresponding analogy to the DNA of a biological entity in engines design is the design specification information, as this defines the key dimensions and features of a given engine family or variant. The body plan of an engine can be thought of as its design configuration and plays the same role in influencing success in the engine's operating environment and being used to categorise the engine type. In this way, an inline four cylinder engine versus a V6 engine might be thought of as two alternative 'body plans' of engine design.

An example of the influence of morphology and survival in organisms is the crab's claw. The claw provides a number of functions including sexual display to indicate reproductive fitness, manipulation of objects in the general activities of life, as a defence mechanism against potential predators and as a means of crushing prey to obtain sustenance. The crabs claw must therefore perform a number of competing functions, with the two most important being predation for survival and display for reproduction.

Female crabs use male crab claw size as a proxy for reproductive health. In a similar manner to display features in other animals, such as horns, antlers, extravagant feather displays, etc., the production of display features is expensive in terms of natural resources and energy consumption. This cost can only be afforded by the healthiest individuals within a population who have access to resources and the ability to defend and sustain them. These are the attributes that potential mates seek in both genetic make-up and support for raising offspring. However, the cost of display can be high.

Display features such as a crab claw, can be large, cumbersome and heavy, leaving the crab vulnerable to other predators. In addition, the cost of display must be limited to what the individual can sustain without jeopardising their own survival. There is therefore a delicate balancing act that must be performed by the crab between not expending too much energy on display, thus risking its own survival, nor spending too little and limiting its ability to successfully reproduce. In order to balance the varying needs of display and manipulation in crab claws, male crab's body plan often draws on sexual dimorphism, with one claw much larger than the other.

The second and arguably more urgent requirement of a crab's claw is in the immediate and persistent necessity of aiding in survival by acting as a tool to crack open the shells of its favourite foods - molluscs and other hard-bodied shellfish. Naturally the mollusc is trying to avoid being eaten, its primary form of defence being a hard shell. In a similar manner to the crab, the mollusc pays a price in energy and resources for having a thick shell structure and therefore seeks a shell that is sufficiently strong to defend against predators but not excessively costly to produce and maintain. The crab, likewise, must develop a claw structure that has sufficient strength to crack open shells without being too costly in resources and cumbersome to carry around. Figure 55 shows the relationship between crab crushing strength and size.

Figure 55 Crab Claw Mass vs Strength - Male Hemigrapsus Sanguineus. Payne & Kraemer 2013.

If the crab exerts too much pressure on a thick mollusc shell, it can crack its own claw leading to a reduced ability to predate or even death through starvation. If the crab does not exert enough force of thick shelled prey, it foregoes a meal that may hinder the crab's ability to survive. In this way, an arms race develops between crabs and their prey, each seeking to improve their chances of survival without incurring too high a price. In *The Evolutionary World* (2010), Vermeij describes such an arms race between green crab along the north Atlantic coast of the USA and their prey, the common periwinkle.

This description implies a certain degree of conscious intentionality that is not actually present in nature. In reality, natural selection simply favours those phenotypic attributes of crab claws and mollusc shells that are best suited to their prevailing environment, including their respective predators and prey.

This process of optimisation of phenotypic attributes and body plans in nature is replicated in the design of human engineered products. In engine design the structural performance of a cylinder block to resolve the combustion and ancillary loads can be inferred from the maximum power output of the engine. This load carrying capacity is directly related to the mass of the block. Figure 56 shows this relationship for a range of automotive engine cylinder blocks derived from benchmark data.

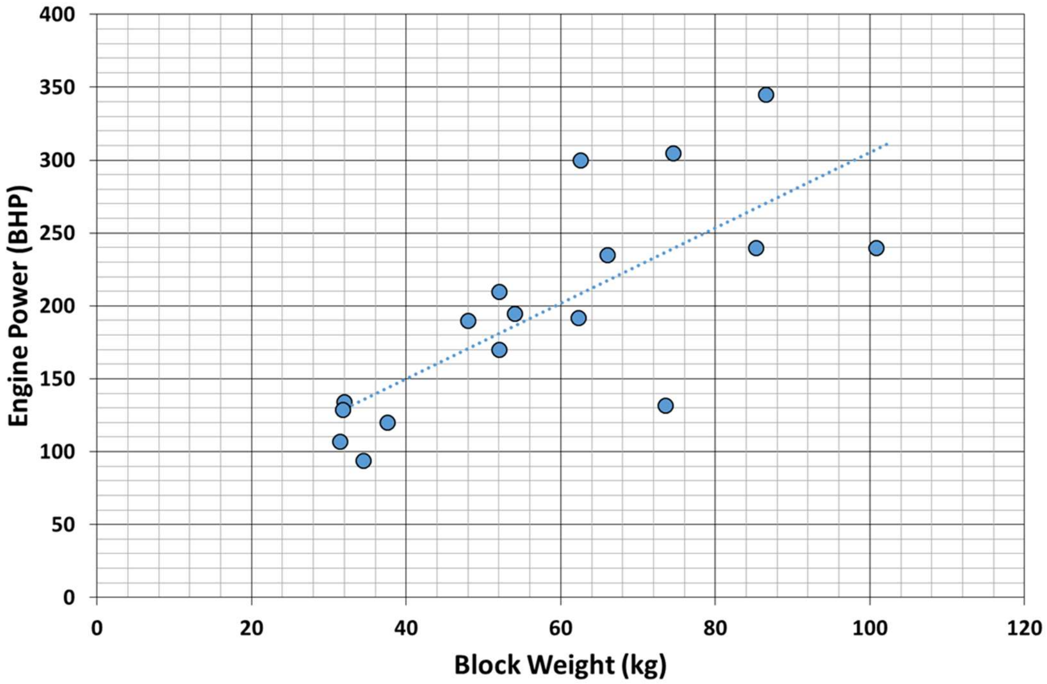

Figure 56 Cylinder Block Mass vs Load carrying Capacity.

The engine designer seeks to minimise mass and therefore material usage, by only providing sufficient structural material to take the expected loads. This is similar to the trade-offs encountered by the crab's claw in nature, where resource usage is aligned with functional need. Too structurally weak a block and it will crack and fail. Too strong a block will be heavy, expensive and wasteful of material, leading to being uncompetitive in the marketplace. In both cases there is a requirement to have some additional capacity above a basal load for occasional expected deviations in a load case. However, in order to be resource efficient, this excess capacity must be limited to what is reasonably expected. The calculation of the degree of appropriate excess capacity is not an exact science and it is this challenge that is the core of this thesis.

2.3.3 Punctuated Equilibria and Fitness

The theory of punctuated equilibria set out by Niles Eldredge and Stephen Jay Gould (1972), describes how evolutionary processes are rarely a smooth progression over time. Rather, there are relatively long periods of little or no change in the phenotypic form of a biological entity, occasionally interspersed by brief episodes of evolutionary development. The evolution of the phenotype body plan over time reflects the selective pressures of the environment encountered by the biological entity.

As environmental pressures of predation, food supply, environmental conditions, etc. change, the surviving populations reflect the best 'fit' of attributes to the current conditions. If conditions do not significantly change over time, there is no selective pressure for phenotypic form to evolve.

Technological and design form changes follow evolution with decent through modification (French 1994, Basalla 1988, Businaro 1983), including the patterns of punctuated equilibria - see section 2.2.3 Drivers for Change and the example of bicycle design (Lake & Venti 2009). The evolution of automotive technologies describes pressure driven change cycles (Mom 2014). Mokyr makes direct connections between punctuated equilibrium theory and technological progress (Mokyr 1990). Observing the modes and mechanisms of biological evolution provides a model for technological evolution (Ridley 2015, Ziman 2000, Basalla 1988, Businaro 1983).

Fitness is a reflection of best match between the biological organism and its current environment. It is a relative condition and bears no indication of 'best' or 'fittest' in any absolute sense. As the environmental conditions change, perhaps due to changing climate, the arrival of a new predator, resource shortages in food supply or other stressors, a previously successful organism may no longer be an adequate 'fit' to the new conditions. Variants of the biological entity that better fit the new conditions will have a higher probability of survival and so there will be phenotypic drift over time (Chevin, Lande & Mace 2010). This is the gradual change of the dominant phenotype form in an ecosystem (Whitman & Agrawal 2009).

Selection pressures play a similar role in engines design. If there is little pressure to change existing successful designs due to static regulations and little competition in the marketplace, designs will tend to stay the same for extended periods (Price 2012, Weertman 2007, Grylls 1963). When shifts do occur in the environment for engines, such as when new regulations occur, or a new competitive design appears, the existing designs may no longer be fit for purpose and there is pressure to adapt (van Besouw, Klostermann & Huijbers 2011, Schulte & Wirth 2004).

All biological entities have some resilience to change. This capacity provides them with the ability to survive short-term variation in conditions. Over the longer term or in cases of significant alteration in conditions, the survival and reproductive capability of entities will result in a shift in fitness of various phenotypic attributes, which will be reflected in the population make up matched to the environment (Moczek, et al. 2011).

Resilience

In order for the species to persist over time the individual members of a species group must survive long enough to reproduce. Living in a precarious environment that is the lot of most biological forms, subject to predation and environmental stress, plants and animals must retain some capacity to deal with shocks and setbacks to their ecosystem. As natural evolution is an outcome of past fitness between an entity and its environment, the entity has no guarantee of success in the future if the environment changes. Environments are in a constant state of flux due to climate, weather, predators, shifts in resource availability and a host of other causes. It is not uncommon that in a complex ecosystem there will be cyclic periods of draught and plenty. If an entity is to survive through these periods of shortage or unusual pressure they must have sufficient reserves of capacity to survive long enough to reproduce and evolve new forms or attributes that allow them to better match the changed circumstances. This 'excess capacity' comes at a cost and must be limited so that it does not endanger the plant or animal's ability for immediate survival by placing an undue burden on resource consumption.

Diamond & Hammond examine the load capacity of a range of animals against basal operating load (Diamond & Hammond 1992). Their conclusion is that animals typically function at a relatively low level of their maximum capacity for most of their functional systems e.g. breathing, digestion and other functional systems, as well as for their structural components (bones, tissue strengths, etc.). Diamond & Hammond's estimate is that animals typically have capacity for 1.2-5.0 times their normal base load.

There is obviously a cost associated with carrying this excess capacity. Not only is it expensive in terms of resources but it is also reflected in body size, mass, agility and other important aspects of the animal's physique. These directly affect an ability to outrun a predator or navigate through the environment successfully. This may result is a reduced capability to survive and reproduce, so must be balanced against the desire to have some capacity to survive unexpected events of uncertain probability. This is directly analogous to the circumstance faced by the engine designer in seeking to balance the need for immediate resource optimisation for the first embodiment of the engine family, versus the desire to ensure that future architectural changes (body plan adjustments in the form of new engine variants) can be undertaken within the capacity of the production equipment, without incurring unsustainable costs of transformation. As there is only a finite tolerance to carry unused excess capacity in each engine unit (incurring additional weight and cost), so there is a limit to the amount of investment in excess manufacturing capacity in production plant and equipment that can be tolerated by the manufacturer.

Related to robustness, resilience is the ability to adapt to change. It is a demonstration of plasticity in systems. The concept of plasticity is biological. Phenotype plasticity is the ability of a phenotype (physical form) to adapt and change to better match its environment (Chevin, Lande & Mace 2010, Price, Whitman & Agrawal 2009, Qvarnstrom, & Irwin 2003). This may involve some physical changes or just behavioural adjustments to a new set of environmental conditions.

Capacity, Robustness and Resilience

Over the long-term evolution will take care of adjustments to match prevailing circumstances, favouring those entities configured best suited to the new circumstances. The real danger for survival comes in the rate of change in the environment. The biological entity needs a short-term capacity to be able to survive and reproduce, albeit in a sub-optimal form, for long enough to allow the population density to shift to better match that of the environmental conditions. This means that the organism needs to have excess capacity in those attributes that require a shift in performance.

As discussed previously with the examples of a crab's claw, excess capacity comes at a cost. In seeking to maintain some sustainable level of resource efficiency organisms cannot afford to carry capacity that is unrealistically large for their immediate needs. Neither can they afford to have insufficient survival capacity to carry them through periods of crisis and need. As an example, at the most simplistic level an animal may require a reserve of body fat to see it through times of lean food supplies or through periods of extended shortage such as a winter season. However, too much body fat is not only inconvenient for agility in movement, to outrun a predator for example, but may also prove to have longer term health effects. This challenge extends across the physical and functional systems in plant and animal physiology, affecting such systems as bone structure, lung capacity, muscle mass and many others. Getting the balance between required reserve capacity and optimal resource management is a key to long-term success (Rosenblum, et al. 2012).

Robustness is the ability of a system to withstand short term shocks and still function. It can be thought of as toughness - an ability to survive damage. Within an ecosystem robustness is one form of the overall measure of a systems capacity to deal with short-term shocks and perturbations in the environmental conditions (Walker, et al. 2005). Having excess capacity provides an organism with a measure of robustness. In engine design robustness of a design might be thought of as an individual engine's capacity to adsorb excess load without failure of the existing design.

Resilience in ecosystems allows them to readily adapt to change (Scheffer, et al. 2001). Resilience is therefore a measure of the flexibility or adaptability of an entity or system to accommodate a new configuration that better suits changed circumstances. Where robustness seeks to withstand the impact of change, resilience allows an organism to continue to function at some operating point away from optimal conditions (Gunderson 2000). The shape of the adaptive landscape maps out the degree of resilience within a system allowing the viewer to see the direction of change that might be possible and those that might prove risky - see section 2.3.4 Adaptive Landscapes. The resilience of an engine design can be thought of as the ability of the base design to be adapted through design changes without significant need for investment i.e. how amenable the design is to modification.

Uncertainty

The design of a new engine starts from the known requirements and from knowledge of the current state of the art in engines designs. The design and development of a high-volume engine through to production can take several years. Section 2.2.4 discussed the lifecycles of engine projects and how a period of 3-4 years may be required from a market need being identified to a product reaching the marketplace. Given the capital-intensive nature of new engines, they are only economically viable if volumes are sufficient to recover the investments made in production tooling and equipment (Kolwich 2012, Ford & Ryan 1981). Section 2.2.3 discussed some of the challenges of dynamic marketplaces (Routley, Phaal & Probert 2011). The engines industry is particularly susceptible to regulatory changes that govern certification in worldwide markets and policy drivers to incentivise technology choices (Walter, et al. 2010). The engines industry is also highly competitive, with over capacity in existing manufacturers and new entrants entering the industry all the time.

Technological change in engine designs is probably at its highest level since the industry was founded. Dynamic environments create a spur for technological development (Abernathy & Utterback 1975). The diversity of powertrain configurations is expanding due to the need to be as efficient as possible in all segments (Automotive Council 2013, Blackburn, et al. 2011). This dynamic means that previous models for market take-up of product are no longer certain. Forecasting adoption rates of new technologies is challenging (Zoepf & Heywood 2012, Valle & Furlan 2011, Twiss 1992). A review of alternative powertrain technology adoption rates shows that they are almost always overly optimistic.

A better mechanism is needed to deal with this uncertainty. The requirements of a new engine design, which may have a production life of 10-15 years, cannot be fully known at the point when the concept architecture is laid down. Changes can occur in technologies, markets, macro-economics and the competitive environment within the production life of an engine family, negating the original assumptions that went into design definitions for the product. Section 2.2.4 showed how engines may evolve over time in unexpected ways. Any new engine design must therefore have capacity to absorb some change, without carrying a severe penalty for doing so. The biological theory of adaptive landscapes provides us with a mechanism for assessing the resilience of engine designs to changing environments.

2.3.4 Adaptive Capacity

The adaptive capacity of an entity and its fitness to its environment can be visually represented through the use of an adaptive landscape. This allows us to gauge comparative fitness of points on a map of related attributes and also to see the shape of the landscape around those points. The terrain of the landscape gives us a rich source of information on how far from the current location a pair of attribute values can deviate before encountering significant changes in fitness values.

The size of planes of equal fitness on the adaptive landscape is a measure of capacity for change in attribute values - see section 4.2 Modelling Adaptive Landscapes.

Adaptive Landscapes

The concept of a 'landscape' to represent the interaction of two attributes was first proposed by Sewall Wright in a 1932 paper entitled *The roles of mutation, inbreeding, cross-breeding and selection in evolution* (Wright 1932). Presented at the sixth International Congress of Genetics in Ithaca, New York in August 1932, Sewall Wright laid out an analogy of a geographic landscape, where the peaks and valleys represent the relative fitness achieved by the interaction of key variables.

Wright proposed the idea of a three-dimensional landscape terrain, the Cartesian coordinates of which indicate the position on a field described by the relationship between two parameters influencing evolutionary success in a biological entity. These might be physical characteristics such as wing length versus body mass; functional attributes such as oxygenation efficiency versus lung capacity or a combination of both. The third dimension of the landscape, the height or elevation of the landscape, is a representation of the fitness of the attribute coordinate combination pair for survival (Wright 1932).

Wright's diagrams that accompanied the paper have been described as "one of the most famous metaphors in the history of biology" (Dietrich & Skipper 2012 p.3). Figure 57 shows the classic first representations of adaptive landscapes drawn by Wright. This diagram shows some of the proposed patterns of genetic drift across a landscape caused by selective pressures (Wright 1932). The use of the adaptive landscape was popularised by the noted evolutionary biologist Theodosius Dobzhansky in several books and articles, subsequently being widely used as a convenient description for the dynamic processes of evolution and fitness in an ecology (Serrelli 2011, McGee 2007, Arnold 2003).

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Illustration removed for copyright restrictions

Figure 57 Adaptive Landscapes. Wright 1932.

The imagery of the adaptive landscape was further developed by George Simpson, proving to be useful in describing how fitness maps to attributes, particularly phenotypic characteristics, but also as a means of showing dynamic changes over time to fitness values and how attributes may 'track' preferential attribute combinations (Simpson 1953, 1944). The influence of Sewall Wright's work as exemplified in 3D representations of landscapes to visualise relationships for fitness and survival, is significant (Coyne, Barton & Turelli 1997, Ruse 1996, Provine 1986). Like all metaphor, it is incomplete and falls down under close scrutiny, being an analogy rather than an exact representation. The uses and limits of the adaptive landscape continues to the present, with conferences being organised to debate how far it can be applied and papers being written on the evidence for its efficacy in application (Svensson & Calsbeek 2012). What is beyond doubt is the utility that the metaphor provides in communicating concepts and relationships in evolutionary drivers, even if quantitative extraction of model data is less than perfect.

The adaptive landscape model can be best thought of a meta-model showing the broad sweep of attribute relationships, rather than the detailed nuance of exact calculation. In this, it sets out the sense of a landscape's terrain, the location of its mountains and valleys, without attempting to map out every hillock or stream. Viewed in this manner it can prove productive in guiding the overall direction of travel, but should perhaps not be relied on to explain every particular circumstance.

Figure 58 is an example of an adaptive landscape showing bill depth vs groove width of the match between the beaks of finches and the morphology of the pine cones that contain the nuts that are a major source of their food. The landscape represents the relative fitness of match between the bird's morphology and that of the pines cones in its environment. A better match between the two means greater 'fitness'. It can be seen that there are peaks and ridge of good fit, interspersed with valleys that are still viable but less well matched. The form of the landscape shows the nature of the relationship between the attributes being considered.

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Figure 58 Adaptive Landscape for Beak and Food Source. Hendry, Millien, Gonzalez & Larsson 2012.

Dynamics in Fitness and Temporal Effects

The survival environment is in a state of constant change, to a greater or lesser extent. Natural perturbations in weather, food supply, water availability, predator populations and other factors influencing health and well-being, create changes in the match between a biological entity's fitness for survival and reproduction and the ecology in which it lives. These effects may be a reflection of the daily cycle of temperature and light or be over a longer period such as seasonal changes. The ability of an organism to adjust to the vagaries of these perturbations is its plasticity (Moczek, et al. 2011, Whitman & Agrawal 2009).

Living organisms have developed a number of strategies for dealing with these cycles of environmental change, including hibernation and life history stages such as the profound changes induced by metamorphosis. It is within the capacity of most organisms to weather the storms of short term change without this impacting the survival rates of populations to the extent that it affects overall population make up. Longer term cycles, such as climate change and more significant shifts in the ecology of a particular environment, will have a marked impact on survival fitness of phenotypes. As the ecology shifts, the attributes that the changed ecology favours will be shown in the population densities of organisms that possess characteristics conducive to survival and reproduction. Evolution is a necessarily slow process, relying on reproductive success in one generation to be passed on to the next, gradually shifting the genetic code of the species.

The adaptive landscape is a reflection of the current conditions encountered in the environment, whether biological in the case of nature or economic in the case of business. The adaptive landscape therefore provides a mechanism to visualise the interactions of influencing factors or attributes on the fitness of configurations or geometric arrangements, whether biological or a human-made design. For a manufactured product, the environment that drives the system ecology can be highly dynamic. Changes in selection pressures can come from competition, resource limitations, the introduction of new regulations; even 'fashion' and other intangible shifts in demand. As the adaptive landscape shifts, the optimal peak for fitness will shift correspondingly. Fitness peaks may rise and fall or shift location over time, under the influences of external factors (Schluter 2000).

As a fitness peak changes magnitude it will influence the degree of concentration of the population across the landscape. Figure 59 shows an increase in fitness value from time period T_1 to a higher value in time period T_2. As the fitness peak becomes more dominant in the landscape the selection pressure to concentrate phenotypic attributes at the peak values becomes more acute. In an engine design, this would be shown as a convergence to a particular technology, configuration or attribute. An example might be the increasing fitness value of fuel injection systems compared to carburation, driven by the need to meet emission certification regulations. Prior to emission regulations being introduced carburettors had a high fitness value due to low cost and ease of operation. With the introduction of stringent emissions requirements, fuel injection fitness values increased in the selection landscape, despite its higher cost and complexity. Once dominant in fuel systems, carburation has all but disappeared as a fuel metering technology under these pressures. This change occurred gradually, in stages, with each phase of emission legislation being introduced and emission levels lowered.

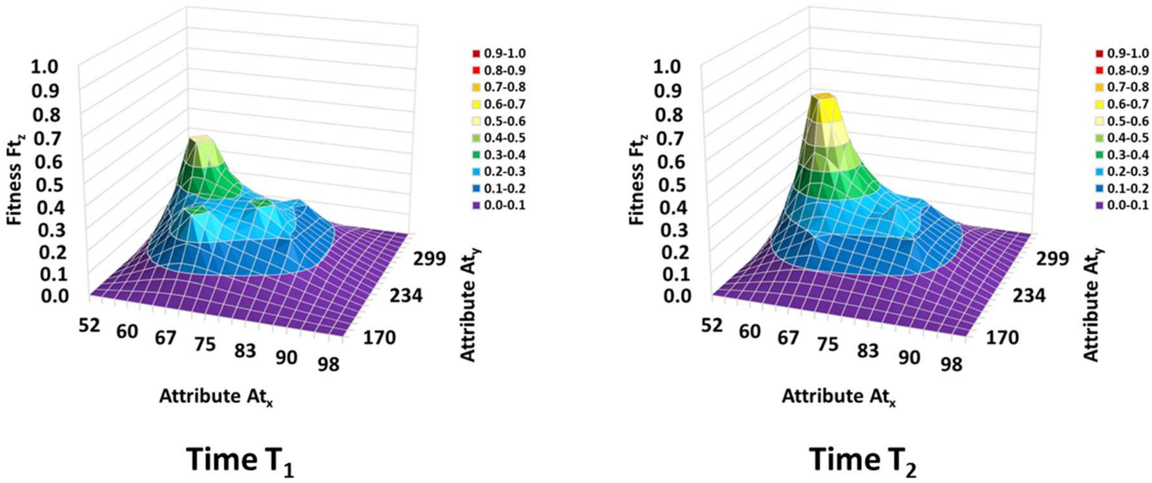

Figure 59 Changes in Fitness Peak Values.

The location of the peak may also move over time, as the fitness values of coordinate points on the landscape changes. Figure 60 shows how a fitness peak P_1 may shift to a new location over time, as the environmental circumstances make a new location (P_2) either more attractive or viable. An example in engine design might be a shift to lower displacement engines in a market, driven by fuel consumption targets or CO2 legislation. Smaller displacement, higher speed or pressure-charged engines are more efficient than larger displacement engines, but also more expensive. As fuel prices have changed over time or in markets where there are extremes of fuel pricing (high or low), the mix of engine displacements reflect these factors. In the USA fuel prices are generally low in world terms and automotive engines tend to be lower cost and have larger displacements. In Europe fuel costs are much higher due to taxation regimes and automotive engines tend to be smaller displacements for the same applications.

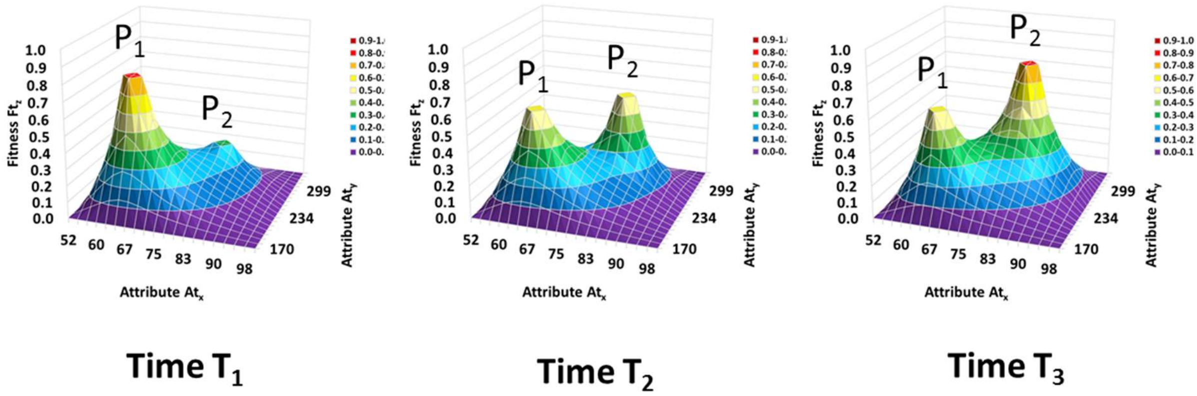

Figure 60 Dynamic Adaptive Landscapes.

The temporal dynamic shifts in adaptive landscapes will be a combination of shifts in peak values and locations. This creates quite a challenge as the engine designer seeking to use the adaptive landscape as a means of planning future product must not only understand the current landscape form but also predict expected shifts in the landscape over the period under consideration. This may include the arrival of new peaks with the introduction of new technologies, such as hybrid or fuel cell powertrains.

Satisficing and Adaptive Landscapes

Herbert Simon's concept of satisficing rather than optimising extends beyond the world of business and can be seen clearly in nature - see section 2.2.5 on Satisficing. Evidence for nature being seen as an optimising engine, favouring the best or most fit from each generation with higher potential for selection and reproduction, can be seen in the development of genetic algorithms as a mathematical optimisation tool (Holland 1995, Mitchell 1999, Pham & Yang 1993). In reality, it is humans that tirelessly seek perfection - nature satisfices. If there is no strong selection pressures nature will continue on a path of least change, as all change comes with both cost and risk. This is why we have plants and animals that have changed little in millions of years, such as the sharks and crocodiles. Other animals have continued to evolve from these progenitors whilst some of the original species continue to replicate, unchanged, in parallel with devolved species. How is this possible, if nature favours 'improvements' through an evolutionary process?

There is no single body plan solution that will satisfy all environments or conditions. Where there is selection pressure to change, biological entities will evolve. This can be remarkably fast. As an example, fresh water fish in Africa's Lake Tanganyika have been observed to evolve in a few hundred generations (Takahashi & Koblmuller 2011). Differing selection pressure can explain why some offspring evolve whilst others can survive to replicate and be successful in their niches without the need to evolve (Weissing, Edelaar & van Dooren 2011). Evolution is a process of matching biological morphology to environments. As the environment changes, the morphology must change to remain fit for survival in that environment. If the environmental conditions are stable, there is no requirement for change in morphology as the biological entity remains a good match without the need to evolve. Evolution involves risk and therefore only occurs as an outcome of necessity.

Note that the plant or animal only needs to be 'good enough' to survive and reproduce, to pass on its genetic material to the next generation. If resources are plentiful and there is little competition, it does not need to be perfect or optimal in any absolute sense. As long as requirements for survival are satisficed there is no benefit in expending energy on change. Designed products reflect this dynamic. Products which continue to perform well in their niche are not subject to change. Product niches that are under higher pressures, such as when a new category or technology emerges, are highly dynamic and exhibit a flurry of design forms before converging to standardised forms - see section 2.2.3 Drivers for Change in bicycle designs.

An example from the engine design world can be seen in the range of engine configurations in Grand Prix Motorcycle racing. Prior to 2002, Moto GP was a two-stroke formula and almost exclusively teams used L4 (inline four cylinder) configuration engines. With a change to the rules from the Federation Internationale de Motocyclisme (FIM) governing body allowing four-stroke engines of 990cc to compete from the 2002 season onwards, a plethora of new engine configurations appeared. These included engines with different numbers of cylinders and varying vee and inline configurations - V2, L3, V3, L4, V4 & V5 configurations were all competitively raced over the following seasons. Prototypes of V6 and L5 engines were also developed but not raced. Manufacturers tested many configurations and arrangements in an attempt to gain advantage in this highly competitive field. Since the initial divergence of engine configurations, teams have now converged exclusively to V4 and L4 formats. On an adaptive landscape, the fitness peaks for these configurations would have shown rapid shifts in location and fitness value during the dynamics of this transition (Cantore & Mattarelli 2004a).

Specialisation Vulnerability

The greater the degree of specialisation in biological species, the more vulnerable they are to changes in the environment. At an extreme, certain species of humming bird have evolved to only take nectar from a limited range of flowers; the flowers in turn, only being able to be pollinated by the humming birds (Cotton 1998). The species co-evolved into an ecological niche. Specialisation in plants and animals means that they have less plasticity to adapt to changes in their environment, particularly changes in their symbiotic co-evolved partner species. This makes them vulnerable to extinction. Plants and animals with greater plasticity and less dependence on other species are more adaptable. They are less optimised for their niche but conversely have greater resilience to change. By satisficing a species adopts the minimal degree of fitness necessary to survive, rather than maximising the amount of fitness possible. This is a trade-off between fitness (survival possibility) and resilience (adaption to change). Both are attributes of long term survival of a species.

If an engine design is developed to satisfy a niche application, it may be less adaptable to changed circumstances. An example of a very specialist design of engine might be a modern F1 race engine. It has high performance in the niche in which it operates (F1 racing), but is unsuitable for not only other applications but also often for subsequent seasons. By comparison a standardised base engine from a company like Cummins, such as the B Series four-cylinder diesel engine range, is adaptable to many uses, including transportation, marine and industrial applications - see section 2.2.5 Strategic Engine Planning. The price paid for this plasticity is a lower absolute level of optimisation in any one application. However, the engine satisfices in all its applications sufficiently to be successful. In this case, the advantages in economics of scale for the B Series across multiple usage applications outweigh the reduction in optimisation in any one niche application.

The particular strategy of optimising or satisficing that an engine designer should adopt will depend on the needs of the particular application and the degree of competitive pressures. The relative fitness values of engine performance, weight, cost, etc., for the application will determine the most appropriate strategy to apply.

2.3.5 The Application of Biological Models to Engine Design

Like any form of analogy, biological models will not always or completely translate to the non-biological world. Care should be taken to understand the limits of the analogy and ensure that it is appropriately applied. However, the theory of adaptive radiation provides us with a framework for assessing the robustness of morphological forms to changing environmental pressures (Meyers & Burbrink 2012, Schluter 2000, 1996).

The evolutionary developments of products replicate the evolutionary development of life forms in nature (Ehlhardt 2016, Egar 2013, Ziman 2000, Basalla 1988). Biological models can consider the dynamics of changing adaptive landscapes and provide the designer with a mechanism to consider satisficing current conflicting requirements whilst maintaining adaptive capacity for future changes.

Whereas engineering design has traditionally been dominated by optimisation of functional targets, natural systems have been required to satisfy multiple demands in dynamic environments (Chowdhury & Taguchi 2016). This latter set of constraints is more aligned with the challenges facing engines designers as they struggle to conceive product to meet ever tighter requirements for financial viability, sustainable use of resources and increasing customer expectations of functional performance (Engel, et al. 2012, Persson 2012, van Besouw, Klostermann & Huijbers 2011).

The concept of fitness landscapes is pertinent to engine concept design in providing a value-based system of evaluating options for alternative design geometries. The use of adaptive landscape metaphors to mechanically designed products provides a unique mechanism for visualising optimization peaks and evaluating options for geometry trade-offs in design. This approach provides a single comparative metric for multi-criteria assessment in design attributes.

2.4 Context and Literature Review Summary

This chapter has laid out the context to engine design and some of the key factors that influence or determine engine concept architectures. It has also presented a biological model as a conceptual framework for considering robustness to change of human manufactured products that follow similar patterns of evolution and development.

High volume engines manufacturing requires high capital investments and those engines many be in production for 10-15 years. During this period, they are exposed to the pressures of change from market dynamics and changing customer expectations, as well as regulatory requirements and technological and competition pressures, which were unknown when the original concept was determined.

The engines industry is now under more pressure for rapid and radical development of alternative architecture configurations than at any other point in its history. The engine designer therefore has the conflicting challenges of designing a product that is as optimised for performance against multiple criteria as possible (cost, size, weight, emissions, power output), whilst considering the future growth needs of the product for different variants and configurations. There is considerable uncertainty in determining future needs for engine architectural development over the manufacturing lifetime of the product. A retrospective look at historical trends shows that some patterns of development can be reasonably predicted, such as a desire for larger displacement variants and a growth in required performance levels. Using these historical patterns and the designer’s knowledge of future trends, it is possible to develop heuristics to guide likely future adaptability requirements.

The chapter has provided a picture of the biological analogy for resource utilisation and how that might be applied in other contexts. The concepts of satisficing, which is not natural to the engineering mind, has been presented. This gives us a philosophy to work with in looking at attribute selection in a new product design. It shows us that 'good enough' in most areas often provides a more globally optimal solution than 'perfect in some, and poor everywhere else'. Adaptive landscapes can give us a visualisation tool for evaluating options and communicating trade-offs. This has not previously been applied outside the biological field, but it shows much promise in being a useful metaphor in concept evaluation.

The challenges of making 'good enough' decisions on key engine architecture dimensions has been presented. The process designers typically follow in coming to their choices has been laid out. We can see that designers are working with incomplete information in the early stages of a design but that the choices they make can have long lasting consequences for the lifecycle of the capital investments made by an engine manufacturer. Engine concept designers currently have a number of strategies that they can bring to bear in optimising investment decisions but when it comes to selection of major engine dimensions, the consequences of lifecycle evolution are usually overlooked or ill-considered.

A proposal for taking inspiration from modelling resources in the natural world and applying it to engine concept design is proposed. The next chapter will lay out a methodological approach for assessing the value of this thesis and applying it to a sample case. The methodology used in the study is presented, with reference to sources of information and constraints on the process.

3.0 Methodology

The previous chapter presented a more detailed context for the engines industry and engine concept design, together with a discussion of how developmental patterns in nature might be useful in building resilience to change in product design. This chapter presents the methodological approach that has been taken to the study, understanding the design process for engine concepts in more detail, considering the constraints of sparse data and developing a modelling technique using adaptive landscapes formulated from von Neumann cellular automata as a means of evaluating adaptability in design geometry. Modification methods to appropriately constrain the generated adaptive landscapes are shown. Finally, a validation process through modelling investment strategies in manufacturing equipment is discussed.

3.1 Introduction to Methodological Approaches

The previous chapter set out the need for a better decision support tool for concept design in considering the whole production life of the product and any architectural changes that might be required over that period. A biological metaphor was proposed, that might prove useful in evaluating trade-off decisions in the design space.

This chapter outlines the approach taken to the study. It begins with a review of the interview and survey process followed, to better understand the requirements for performing a concept design activity in the engines industry. The challenges facing designers were explored and the attributes of a tool, process or method to assist them in their work is discussed. Sources of secondary data are described. The limitations of data availability are outlined and the nature of input data used for the study are described.

The chapter then goes on to discuss the use of sparse data in the early stages of an engine concept design. Appropriate modelling techniques for generating adaptive landscapes and the selection of a suitable modelling environment is discussed. The approach to modelling adaptive landscapes and the application of fitness values are covered. Finally, validation of the design options chosen are presented, with the modified Norton-Bass adoption curves being proposed as a means of evaluating viable investment strategies for manufacturing plant and equipment.

3.2 Multi-disciplinary Research

The design and development of products involves a multi-disciplinary approach. For a product to be successful in the marketplace, it must not only achieve technical excellence, but meet a real market need, be easy to manufacture and distribute, be able to the appropriately supported in the field and produce a financial return for the investors (Ulrich & Eppinger 2015). Product development teams are therefore used to involving stakeholders from different disciplines and backgrounds into the development process, to ensure that a balance of requirements is successfully delivered by the final product specification (Verhagen, et al. 2012).

Multi-disciplinary approaches have been applied to flexibility in engineering systems in recognition that this issue represents a complex, interactive process that needs to be tackled from a systemic perspective (Saleh, Mark & Jordan 2009). The use of multi-disciplinary approaches has been extended to optimisation of engineering systems (Alexandrov & Hussaini 1997). These methods ensure that a broad perspective is taken of the different disciplines that can be allied to optimising engineering design solutions.

Beyond taking an inclusive view of engineering and business discipline inputs into design specifications, there are benefits to learning from other areas of knowledge entirely. This is a process of seeking similarities in problems in one discipline area to learn innovative approaches that might be applied to similar problems in another discipline. It has been recognised that the most innovative solutions can now often be found at the liminal spaces or overlapping areas between traditional, somewhat arbitrary, disciplinary boundaries. The challenges of multidisciplinary research are that it requires expertise to be draw from many areas, which must be evaluated for alignment and relevance (Cuevas, et al. 2012). Theory developed in one discipline may not translate seamlessly to another. It is often the ideas and meta-processes of a theory that offer the most value in helping clarify thinking in another subject area. Theories can be applied analogously to provide a framework for thinking about problem areas (Businaro 1983).

In particular, learning from nature and evolutionary processes has been popularised by the work of Holland in genetic optimisation processes (Bentley 1999, Holland 1995), Benyus in biomimicry (Benyus 1997) and Ridley in considering the alignment of evolutionary processes to many other aspects of human endeavour, including banking and finance, social policy, engineering optimisation and many others (Ridley 2015). Nature inspired design has become a rich area for inspiring novel solutions in engineering design (Brebbia & Pascolo 2002, Martin 1995).

Evolutionary theory has been shown to describe the developmental processes of human engineered products over time (Ehlhardt 2016, Anderson & Tushman 1990). The dynamic of punctuated equilibria in designs can draw directly from theory developed first to explain the morphological development of plants and animals (Eldredge & Gould 1972). Biological evolutionary processes have been mapped to manufacturing environments to explain how changes over time follow patterns of development that can be mapped and predicted (AlMaraghy, AlGeddawy & Azab 2008). Darwinian models of evolutionary development can explain the controlling mechanisms of developmental drivers for change (Hodgson & Knudsen 2010) and how evolution fitness searches may be used as a means of optimising configuration selection (Lake & Venti 2009, Jones 1995).

The pressures for resource efficiency in nature and the need to be fit for survival in a dynamic environment are replicated in the ecology of an industrial context (Ehrenfeld 1997). The metaphor of an ecology to support a product and the pressures for survival under changing conditions has been explored from a financial, organisational and product design point of view (Pizzol 2015, Nieuwenhuis & Lammgard 2013, Nelson 1994). By taking natural processes as a model for resource efficiency, balanced with a need for adaptive capacity, we can consider how we might obtain more robust designs for manufactured product (Arthur 2009, Ricklefs 2008, Vermeij 2006, Vogel 1998).

The methodology used in this study has been to take a natural meta-model of biological morphological optimisation to satisfice the requirements of resource consumption and survival capacity under limited uncertainty - namely adaptive landscapes, and apply these to the design choices for the key dimensional architectural dimensions of new engine concepts. In order to do this, we must first understand the needs of the new engine program and the working methods of engines concept designers.

3.3 Engine Designer Interviews and Survey

Understanding the process of the concept design of engines enables us to identify opportunities to optimise the design configuration and make it robust to future changes. In order to understand the requirements of engines concept designers and the decision-making process to bring a new engine to market, a series of interviews were conducted. Engineers and new product development professionals involved in the concept design of new engines were sought, to establish what their key decision-making processes were and what concept designers were looking for in supporting information regarding engine architecture configuration studies.

Through a network of contacts established through the author's career in engine design, product development professionals with experience in the engines industry were selected. Engineers and key product development stakeholders known to have experience in the configuration of new engines were approached through personal contact - see Appendix A Interviewee Profiles for details of the interviewees background.

A survey of engineers working in engines design and development was conducted to establish typical levels of involvement with concept design activity and the key priorities for engineers on executing engines programs. This survey cohort represented engineers involved in stages of engine new product development conducted after the concept was established. They were typically involved in later stages of development through to product launch to market and production support, including design and specification changes throughout the production life of the engine. The information gleaned from these interviews and survey were used in section 2.2.3 as context for the research study.

Product Developer Interviews

A total of 19 engines new product developers were interviewed, either in person or by phone. Interviews were semi-structured to allow for open responses. Prompt questions were asked on the scope of engines projects and in particular the challenges of managing the engine lifecycle and the decision-making process used in bringing a new engine to market.

Interviewees were drawn from a mix of sub-discipline backgrounds within the engines industry, with experience of the engine concept design stage of an engine program. Designers (n=9), are directly involved in concept design work and the layout and arrangement of new engine configurations. The project managers interviewed (n=6), were experienced engineers whose current primary responsibility was leading the design and development activities on a project. They are responsible for delivery of the project scope, on time and within budget. The final group of interviewees were marketing professionals (n=4), with principal responsibility for marketing liaison with engineering functions for new product development. They act as the voice of the customer in the definition of engines programs.

The average professional experience of the interviewees was 16.1 years (Std. Dev.=6.03, Max.=30, Min=6). This range of professional stakeholders involved in the engine concept configuration process, allowed for a complete picture to emerge of the influences on concept configuration and the decision-making processes involved in trade-off decisions. It also enabled consideration of the timing of decisions and when important design geometry gets fixed in engine design.

Both engineering consulting companies (n=10) and engines manufacturers (n=9) were involved in the study. In some cases (Cosworth, Lotus & Ricardo) the company is both a consultant to external clients, as well as a manufacturer of low to medium volumes of special engines (volumes of 500-5,000 units per annum). These companies were categorised by the major area of activity (usually consulting).

Companies represented in the study were:

- Ricardo Consulting
- Chrysler Motor Company
- Romax Technology
- Lotus Engineering
- Mercury Marine
- Harley-Davidson Motor Company

The combined relevant new engine program experience of the interviewees covered 84 projects over a period of 30 years. The majority of these were completed in the last 15 years. Each interviewee had completed between 2-8 new engines programs.

The interview questions focused on understanding the new product development process (NPD) for engine programs. For the purposes of the study a ‘new’ engine was defined as a program that involved either a clean sheet design not based on a previous engine or a substantial change to geometry of the base engine design of a current product e.g. changes in displacement, bore/stroke, numbers of cylinders, etc., that would be recognised as a unique geometric variant. These levels of geometry change to the key engine dimensions will have a significant effect on manufacturing tooling and equipment. Derivatives or versions of engines that did not involve base engine geometry changes, such as a performance or emissions derivative that could be achieved through minor or ancillary component changes or recalibration, were not included in the category of ‘new engine’, as these would not involve significant changes to production equipment such as transfer line systems and dedicated machinery.

Once the concept design decision support tool was developed (see section 3.6.2 Adaptive Landscape Modelling), the modified adaptive landscape (PFAL) process was validated by a sub-set of six of the product designer cohort. They provided feedback on the utility and potential adoption of the process to future engine concept design projects – see section 4.5 Engine Designer’s Perspective.

Survey of Engines Development Engineers

After the engine concept design work has been fixed and initial geometry selected, the design is passed to a larger team of engines engineers for detail analysis, refinement and development. In terms of project time and resources, this represents the majority of an engine engineering program. However, major architectural geometry rarely changes after the concept has been passed on to the main NPD team. Once the concept is fixed, the engine goes through an extended period of refinement and development through simulation, computer analysis, testing and validation. The design geometry and the final specification for the engine will evolve over this period, but the constraining architectural geometry (bore, stroke, block height, connecting rod length, etc.) are already determined a fixed. It is this architectural geometry that limits future dimensional growth of the engine, but it is the main NPD team that are responsible for further developments to the engine, including design changes and variant developments during the engine's production life, that are constrained by the concept architecture that they are given by the concept designers. Understanding the impact that fixing engine major geometry early has on subsequent design change to the engine allows us to put the consequences of the concept design decisions into perspective.

The sample of engines engineers surveyed was selected from students enrolled in a master in engine systems degree program at the University of Wisconsin - Madison in the USA. All students on the program are practising engineers, involved in the design and development of engine systems. The program has a requirement of at least five years post-graduation work experience in the engines industry, but the average professional experience level is ~12 years, with some students having 20-30 years' experience in the engines industry. The program is aimed at developing the skills and abilities necessary to become a chief engineer in engine design, with most of the students identified by their employer as high potential and are sponsored through the program as such. This cohort represents engines engineers with experience working in engine development who aspire to become engine architects creating concept designs for new engines.

The students are employed in a range of engine applications industries from large marine and locomotive engines, through industrial and agricultural engines, to high volume automotive engines and racing engines. Primarily employed by engines manufacturers, there is also representation from engineering consulting companies and tier 1 suppliers to the engines industry.

An on-line survey tool (SurveyMonkey) was used to solicit anonymous inputs from the cohort of incoming students between 2008-2016. Over the period of the survey 119 students were invited to participate. Usable returns were received from 69 participants (~58%), providing sufficient data to be able to draw general conclusions on typical engagement levels with concept design and the types of engineering programs undertaken by engines engineers in their professional practice.

The anonymous survey results were discussed in seminars on engines programs and trends in engines engineering undertaken by the cohorts over a summer residency program each year. This allowed some clarification of responses to place the data in context and anabled checks of validity to ensure that anomalous responses were identified and adjusted.

The results of the survey have informed the work of this thesis and have been incorporated, as appropriate, at various points throughout the study – for example see section 2.2.3 Drivers for Change, 3.61 Modelling Platforms & Figure 17.

3.4 Use of Secondary Data Sources

A number of secondary sources of data have been used to understand the parc of existing engines and general trends in the engines market. Historical data is available on the population of engines configurations, displacements, features and principal geometry, as well as trends in engine specifications over time.

Data on a range of aspects of the engines industry are produced by interested parties and are made available through trade bodies, research institutes or through collaborative benchmarking activity. Publishing organisations, such as Ward's Automotive, Automotive World and The Economist, have developed market and industry intelligence units to gather data from a range of sources and compile it for publication. One of the most common methods of getting input data for these organisation's publications is by direct contact with manufacturers and suppliers to get estimates on production volumes, sales value, engine configurations, technologies being developed, trends in the market and customer demand. This has the advantage that the data analysts can use a consistent methodology and definitions of what data is to be included and in what format. However, it is still open to some variance in interpretation and reporting, between the different publishers and their reports. These reports are made available through subscription or published in summary form as part of a news service or a special issue of a trade publication.

Another method adopted by analysts is a Delphi approach, using the input of selected experts to make estimates and predictions of trend forecasts. This method uses an internal consistency so is often better for comparative analysis, but has the disadvantage of limited access to a wider range of inputs. It is therefore potentially more inaccurate in absolute terms, but more accurate in relative terms e.g. overall production volumes may be in error but proportional production volumes between manufacturers may be more accurately represented.

Trade bodies such as the UK's Society of Motor Manufacturers and Traders (SMMT), play an important role in gathering industry data on a non-competitive basis and sharing it amongst members. Institutional societies such as the Society of Automotive Engineers (SAE), play a similar role, being both a learned society whose primary goal is the dissemination of technical papers, presentations, conferences and exhibitions; but also providing information services on the engines market to its members.

Market data and professional information services companies, such as IHS and Markets & Markets, produce comprehensive market analysis and trending data on technologies and industrial output. These reports can be purchased individually, but are expensive, at typically ~£4,500 for a sector report. The cost is partially a reflection of the time and effort required to gather the necessary data and compile an authoritative report and the limited market for such reports, which means they may only be able to sell a few dozen copies to automotive OEM companies, financial analysts and marketing professionals.

Automotive consulting firms such as Ricardo, MIRA, AVL and others, also have information service divisions that specialise in gathering trends data and preparing industry reports. These types of service are generally aimed at bespoke consulting research in response to a direct customer request, but occasionally collaborative research projects may be undertaken for several clients who have a shared interest in the data. In this way, the costs of the activity can be amortised across all of the study participants allowing them to get access to data that might not otherwise be economically justifiable.

Government departments also carry out their own data analysis on trends in technologies and industries and make this available to a public audience for the mutual benefit of developing markets and helping industry. This can also be a mechanism to stimulate development of new products or the wider take-up of an existing technology that aligns with a policy direction, such as electric or hybrid vehicles usage. Government sources have the advantage of access to government statistical data from official returns, which can be used to look for trends and patterns in consumer behaviour. With the rise of 'big data', this is becoming an increasingly important source of information.

Internal research is often conducted by OEM and consulting companies for their own use. This may be in support of a particular project or activity and is usually undertaken when alternative sources of data are not available, as it can be expensive and time consuming to produce. Internal reports therefore tend to be more tightly focused on specialist areas of interest rather than more generic studies of industry status and trends.

For this study, a wide range of published and unpublished materials were used to establish trends in engines configurations (see section 2.1 Introduction to Engine Design), and as inputs into benchmarks for the analysis of adaptive landscapes. Trade publications were used for trending data over a period of the last 10-15 years, particularly in the areas of market expectations and acceptance. Trade body reports and markets data were purchased from information providers, where possible, although some of the data proved beyond the meagre budgets available for this study. The author has had access to internal reports at a number of consulting companies and has used data from those sources, within the constraints of confidentiality and commercial limitations. Wherever secondary data sources have been used, these have been directly cited and identified as the data source in the body of the thesis. Attempts have been made to use the latest available data in all cases.

3.5 Working with Sparse Data

One of the major challenges of mathematically evaluating design concepts is a lack of detailed data at an early stage in the design process. In the beginning of the design activity, much remains to be defined and those aspects of the design that have been established are yet to be tested against all the criteria required to meet the program objectives. These include requirements not only for functional engineering objectives (weight, performance, emissions, etc.), but also marketing, manufacturing, legal, business and a host of other objectives. The concept designer must find a way to progress the design in a meaningful manner, whilst remaining open to adjusting parameters and evolving options based on feedback from stakeholders and multi-criteria evaluation.

Mathematical modelling in the biological sciences often relies on sampling of data points from the field. Due to scarcity of samples or inaccessibility caused by geography or environment, it can be a challenge to collect as large a sample size as might be considered statistically desirable. However, useful insights on modelling populations, distributions and fitness to environmental conditions have nonetheless been developed in the biological sciences. These techniques can be applied to engineering in areas similarly affected by availability of sparse data.

The starting point for a new product is usually a similar product that has gone before. The engine DNA in terms of configurations, technologies, materials and manufacturing process, can be drawn from a current or past product of the company, benchmark data from similar or competitor engines, donor products or prior advanced research activities. These concepts starting points are then moderated by consideration of the particular constraints of the company and the particular needs of the project.

These constraints may be the available budgets or resources and in particular the investments already made in plant and equipment.

Due to the high investment usually required in the manufacture of a product such as an engine, a somewhat conservative approach is taken to engine designs. In order to reduce risk, the engine designer will work with known quantities - aspects of the engine that are familiar to the designer and in the adoption of which, they can have confidence in the ability to be able to successfully deliver the product on time and budget.

Observation of engines programs shows a tendency for novelty at the advanced research and development stage that gradually gets watered down through the development process, so that the product at launch may be a very different specification to the its earlier design embodiment. One example of this from the author's experience was a program worked on for a major automotive manufacturer in Europe, one of the so-called 'big three' automotive companies in the late 1980s. Early advanced engineering versions of the engine were of a twin camshaft, four valve/cylinder, all aluminium engine with variable valvetrain and advanced electronic controls. If launched to market in the advanced configuration the product would have been best-in-class for weight, performance, emissions and noise. Through the design to production process, considerations of cost, component sharing, as well as utilisation of existing plant and equipment, came to dominate the decision-making process. The resulting product was launched to market as a single overhead camshaft, two valve/cylinder engine with iron block and minimal variable controls. A higher specification variant was also produced, but in lower numbers and at considerably higher costs due to limited volumes effecting the economies of scale for that variant. The product was competitive at launch, but not class leading in any one aspect. A better understanding of the existing product and trends in engines configurations may help avoid starting an initial design concept without taking into account pragmatic factors that can affect key geometry architecture from the beginning. It will also show the proposed concept in context and the areas of the engine design adaptive landscape that are opportunities for exploitation e.g. areas of the adaptive landscape that are feasible, but currently unexploited by competition.

3.6 Design Space Modelling

A design space is a two-dimensional representation of possible combinations of design parameters. A definition by Kang, Jackson & Schulte states design space modelling as "…the activity of exploring design alternatives prior to implementation" done through evaluation of a map of alternative combinations of the parameters under consideration (Kang, Jackson & Schulte 2010 p.33). The design space is characterised by regions of feasible design where the selected parameter values will result in a viable specification and infeasible zones where the selected parameter values will either not meet target requirements or otherwise cannot be realised within the constraints of the design.

Design spaces are used extensively in concept design activity as a means of gaining early clarity of the bounds of parameter selection (Steadman 2008, Ziman 2000). They can be used to identify limits to designs, to plot existing known feasible designs and to explore the areas of opportunity presented by currently infeasible regions. Regions of the design space will be feasible or infeasible depending upon the parameters selected. For example, a position on the design space for the geometry of a component may be infeasible in one material as it may be too weak to withstand expected loads, but feasible in another, higher strength material option. It is therefore important to understand the context of the design space and any assumptions that have gone into the evaluation.

Figure 62 shows a representation of the principal features of a design space. The diagram indicates the position of both feasible and infeasible solutions from analysis or test data. Boundaries to feasibility can be overlaid on the design space, against criteria for design constraints (Material 'M_1', Material 'M_2').

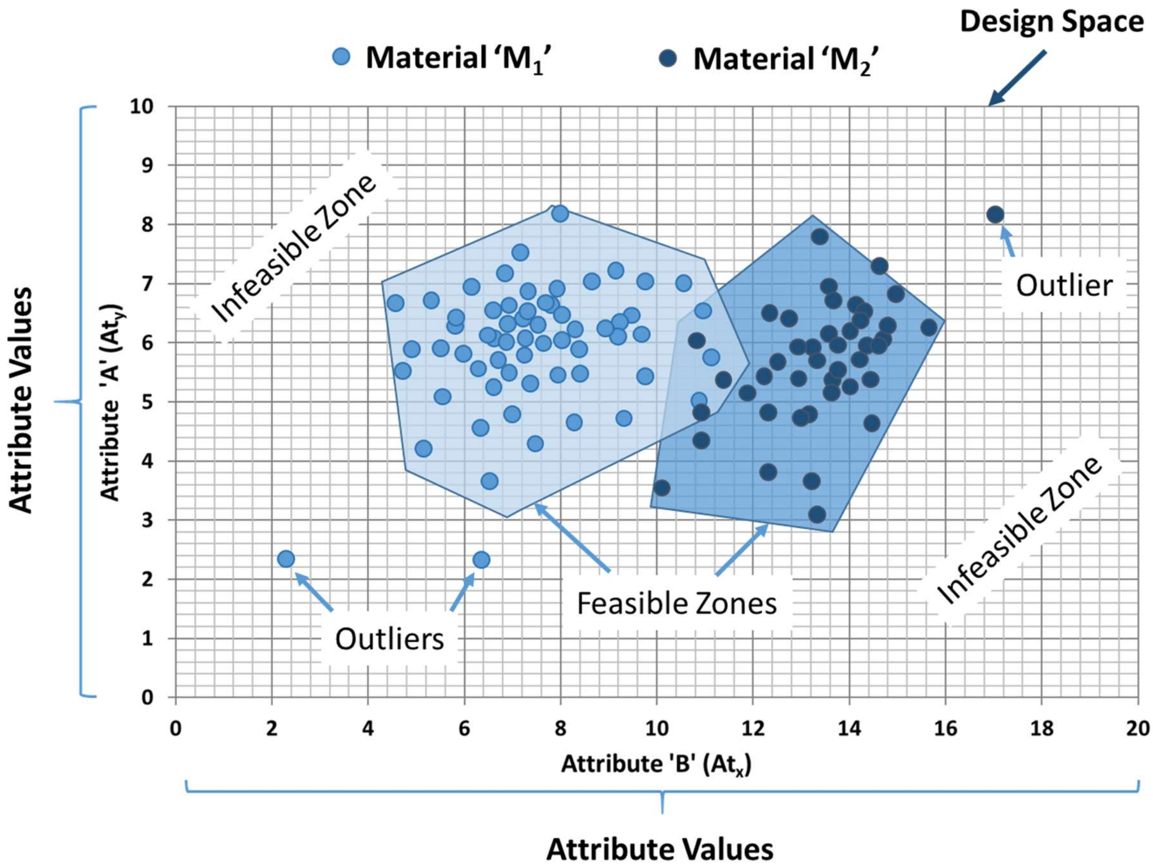

Figure 61 Example Engine Design Space.

Built from sparse benchmark data, the design space can be used to derive fitness values for the parameters under consideration, from the known feasibility of regions of the map.

3.6.1 Cellular Automata

Cellular automata are used to model the relationship between adjacent spaces. A design space can be divided into a series of cells. Each cell can have a value ascribed to it which represents a fitness for that location. The cell value will be determined by the particular properties of that cell location, but also by the values in the adjoining cells (Toffoli & Margolus 1987). Cellular automata can be used to create maps of surfaces that are formed by proximity relationships between neighbouring cells (Codd 2014).

In analysis of product design space, cells can be used to define each position on an attribute map. The unitary values of the attributes define the cell locations in a

Cartesian form. The granularity of the cell matrix will be determined by the attribute values and the required resolution to evaluate the generated neighbour cell values. A 20x20 cell matrix was used in the analysis of design spaces for this study. A higher cell count would provide more surface resolution, but take longer to resolve and not provide any more interpretative information.

Cell automata are created when cell values are calculated from relationship algorithms of neighbour cells. Two neighbour cell algorithms were evaluated, the von Neumann neighbour grid using four immediately adjacent cell values and Moore's neighbourhood model which uses the eight cells surround a target cell as inputs into the target cell value calculation. In each case, the values in the adjacent cells (four for von Neumann, eight for Moore) are averaged to provide the cell value for the target cell. The cell calculations are self-referential i.e. adjacent cell values both influence and are influenced by each other's values.

The Excel program was set up to allow cell self-referencing and iterate to stable state conditions. Iterations were completed in stages, so that the formation of the fitness surface generated could be observed - See Appendix C for screen shots of the process.

von Neumann Neighbour Models

The model iterates using a von Neumann neighbour averaging algorithm suited to cell automata, used in repeated iterations to interpolate between fixed points. For the purposes of this study, a logarithmic decay profile was applied from the fixed points. Figure 63 shows how the cell values are calculated. Cell T_n represents the cell whose value is to be adjusted through iteration with values of the cells immediately surrounding it. Cells $P_1 \ldots P_4$ are averaged to create a new value for T_n. This applies to all cells, except the benchmark points, which are known values and the 'anchor' cells. These anchor cells are cells with fixed values, usually set to zero, to force the surface to be contained in a bounded region at the edges. The zero values are placed at points of known infeasible coordinates. This process is iterated until convergence occurs and cell values settle to stable values. The number of iterations to convergence varied dependent on the complexity of the surface and the relative variation of fitness values.

Steps if 1,000 calculations were used per cycle, with convergence to a stable surface after 30,000-50,000 iterations (30-50 cycles).

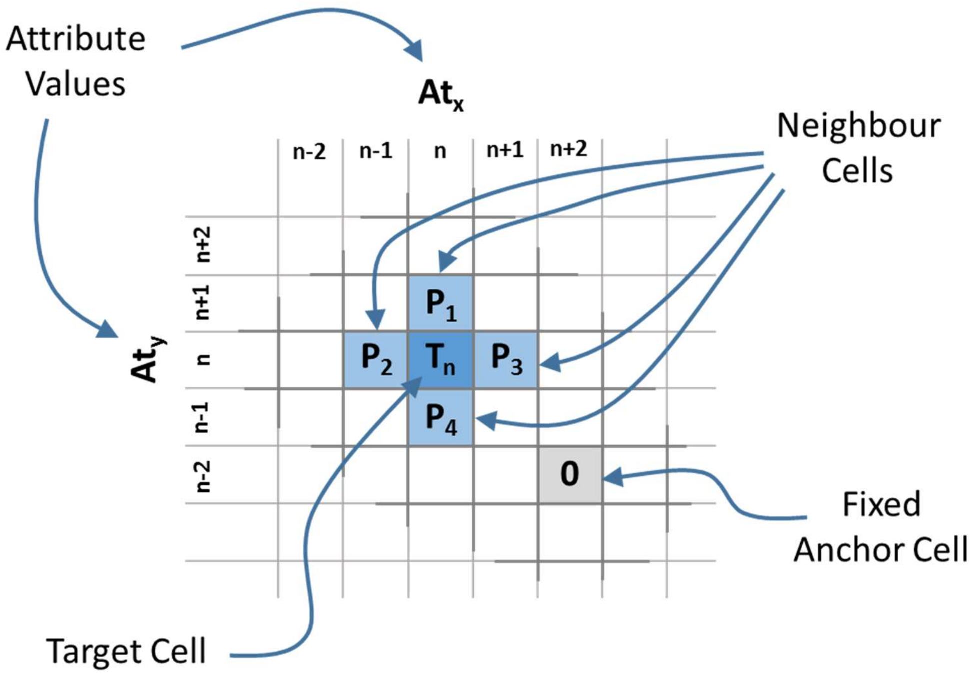

Figure 62 von Neumann Neighbour Algorithm Nomenclature.

Modelling Platforms

In the selection of a suitable modelling platform for evaluation of concepts, emphasis was given to tools and software that would be ubiquitous and already familiar to most engineers. A choice was made early on in the study to avoid specialist software that would require investment in software purchases and additional training by the designer. The rationale for this approach was to enable as wide an adoption of the process as possible by removing barriers to the technique being applied to projects. From both personal experience of the pressures of working at the fuzzy front end of product development and through interviews with concept designers in the study - see section 4.5 Designers' Perspectives, it became clear that at the point where concept evaluation tools are required there is neither the appetite nor the time to upskill to a new process. Designers are looking to focus their time and resource on finding a viable engine architecture that will meet the project objectives, not on learning new tools or conducting extensive searches for new information.

The frequency of new engine programs is relatively low, even within the consulting community. An evaluation of project types at three engines engineering consulting companies conducted as part of the survey of engine development engineers - see section 3.3, indicates that <10% of projects undertaken involve a base engine geometry change. In engine manufacturers (OEMs) it is not unusual for a new engine program to only come along every 10-15 years. Indeed, many engines engineers may only work on one or two new engine programs in their career; the remainder of their career being engaged with projects involving updates, improvements, enhancements or development of existing products. This fits in with the essentially evolutionary process of engines development over their long production lifecycle.

The result of designers having such an infrequent opportunity to work on new concepts means that if specific tools and software were developed that were unique to this stage of the product process, they would be in danger of always being inefficiently applied. The designers would no sooner progress up the learning curve of the tool when they would be putting them to one side to await the next new concept project, possibly several years away. It is therefore essential that methods and processes that are intuitive and based on familiar tools are made available to the designers to enable rapid and confident application.

Several standard modelling environments were considered for the concept evaluation tool, including Matlab, MathCAD and Microsoft Excel. An evaluation of statistical analysis and visualisation tools, including Tableau, XLStat, Origin and NCSS was also conducted. Whilst some of these tools proved to have more sophisticated modelling and analysis capability especially in the area of curve fitting, smoothing algorithms and visualisation, it was decided to carry out the base modelling in Microsoft Excel due to its availability and ease of use for most designers. Any model that could function in Excel could always be ported to other, more sophisticated programs as a further refinement of the process.

3.5.1 Benchmarking

The most common approach to establishing product specification requirements for new engines is to evaluate the current product offerings of competitors. This provides context for the competitive landscape and defines the current ‘state-of-the-art’. This is a long-established part of the engine design process, going back to the first era of IC engine design. Figure 61 shows part of a table of benchmarking data on 228 engines laid out as the first chapter in *Aero-Engines, Design & Practice*, published by Andrew Swan in 1938. This is recommended as the start of the design process and categorises the engines into 34 general configurations. The average number in each category is 6-7 engines, which provides a sparse data set to establish a feasible design space (Swan 1938).

Aston University

Illustration removed for copyright restrictions

Figure 63 Sample Engine Benchmark Data set. Swan 1938.

One obvious limitation of this approach is that it is backward looking and does not take into account future trends and developments. Given that engine design programs can be in development for 3-4 years from concept design start to launch, there is a real risk that technologies, market expectations and competitor products will have moved on from the current status quo. When combined with a potential production life of 10-15 years for the engine, we can see that the concept designer is wrestling with coming up with a concept configuration that will remain competitive and relevant up to 20 years after the initial concept configuration is fixed.

Benchmark data can provide a good starting point for establishing trends in engine designs and determining what configurations might be acceptable to the marketplace. Data on current products configurations is publicly available from a number of sources, including trade publications, manufacturer's websites and marketing materials, as well as specialist producers of information services - see section 3.4 Secondary Data. Engines designers can also generate their own data from a technical evaluation of competitor products and many companies have a well-developed benchmarking process to continually keep appraised of developments in their field. This may involve a benchmarking study of competitor products through testing and evaluation of sample engines obtained for this purpose. This activity is often done prior to concept layout work being started, to establish targets for the concept designs they are being evaluated against.

For this study, a number of data sources were used to provide input data to create adaptive landscapes of key design parameters. These have been referenced where used. When choosing sparse data, it is important to ensure that the data selected is representative of the expected population. This can open the researcher to issues of bias, including confirmation bias - see Appendix B Types of Error.

The concept designer needs to be able to progress the design of the engine architecture and layout, using limited information. Adaptive landscapes in ecology studies provide a means of visualising the feasible population extent from available sampled data from the field. Applying this technique to sparse competitive information data from benchmarking and exemplar engines has the potential to provide designers with a clearer map of design options from available information at the earliest stages of an engine's design development.

3.6.2 Adaptive Landscape Modelling

Adaptive landscapes provide a useful means of visualising the design space of the engine attributes under consideration. Using sparse data, the designer can create an adaptive landscape that will show the areas of the design space with the greatest fitness to the desired objective targets. The principal of an 'adaptive' landscape is that that is shows the potential to move across the space to suit changed circumstance. System architectures can be evolved using the adaptive landscape as a guide to the opportunities for reconfiguration and the limits to change (Engel, et al. 2012).

Once established, landscapes can be subsequently modified to highlight feasible zones - Modified adaptive landscapes (MAL).

Adaptive Landscapes Generation

The process of creating an adaptive landscape using a von Neumann neighbour algorithm to connect the landscape surfaces by filling in the data points between the known sparse data, is as follows:

Stage 1: The candidate model surface data is estimated from a sparse set derived from benchmarking information or published design specifications. It is also possible to perform a speculative analysis based on projections of configuration data. These may be generated from any of the well-established forecasting techniques, such as trend extrapolation or Delphi methods using expert opinion. As with all such forecasting approaches, care needs to be taken with the degree of extrapolation involved.

The extent of the design space is determined by the designer based on experience and an evaluation of the particular constraints of the application under consideration. Some knowledge of the characteristics of the design variables is essential in using the model with intelligence. Thus, the initial data points are selected and then moderated by the designer to ensure validity and applicability to the current project under consideration. Figure 64 shows a sample set of benchmark data for engine performance and cylinder block weight values in the data set of sparse information being used for a model.

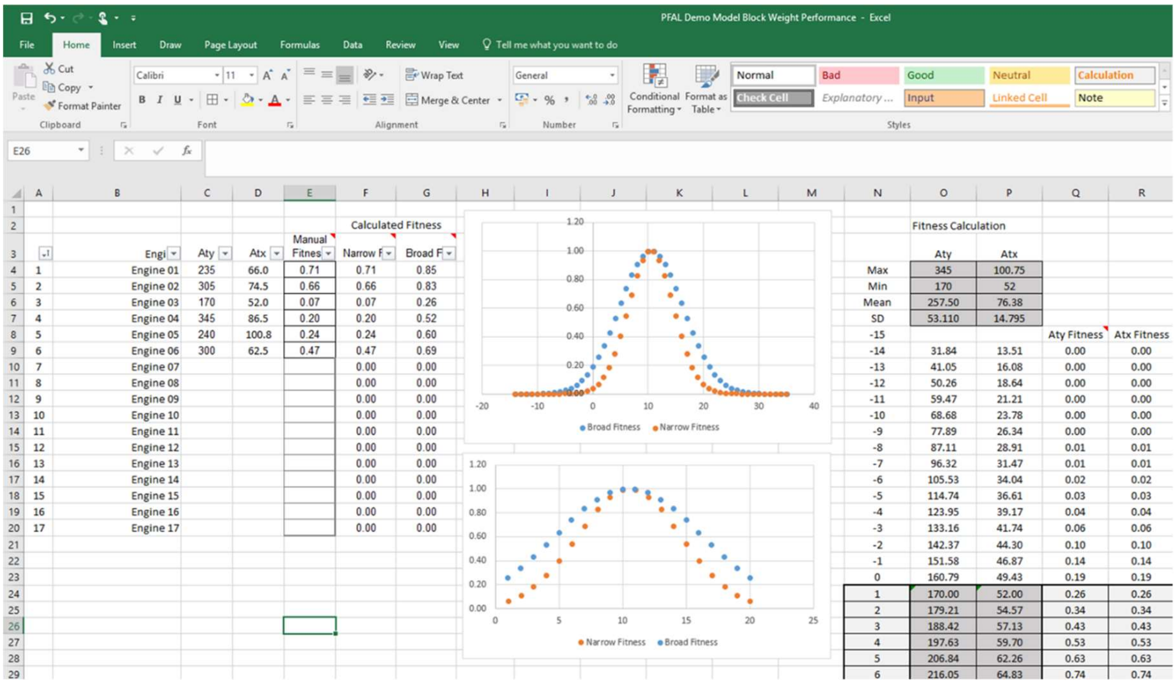

Figure 64 Sample Benchmark Data.

The benchmark or candidate data is entered into the appropriate co-ordinates on the design space map. These become the fixed points of the adaptive landscape and represent known, real embodiments of feasible designs or in the case of projections, reasoned estimates of feasible designs. Figure 65 shows the starting point of the design space map with the initial sparse data points entered at their respective coordinates. The adaptive landscape generated is shown alongside the design space map. At this stage, the adaptive landscape consists of narrow peaks of single value.

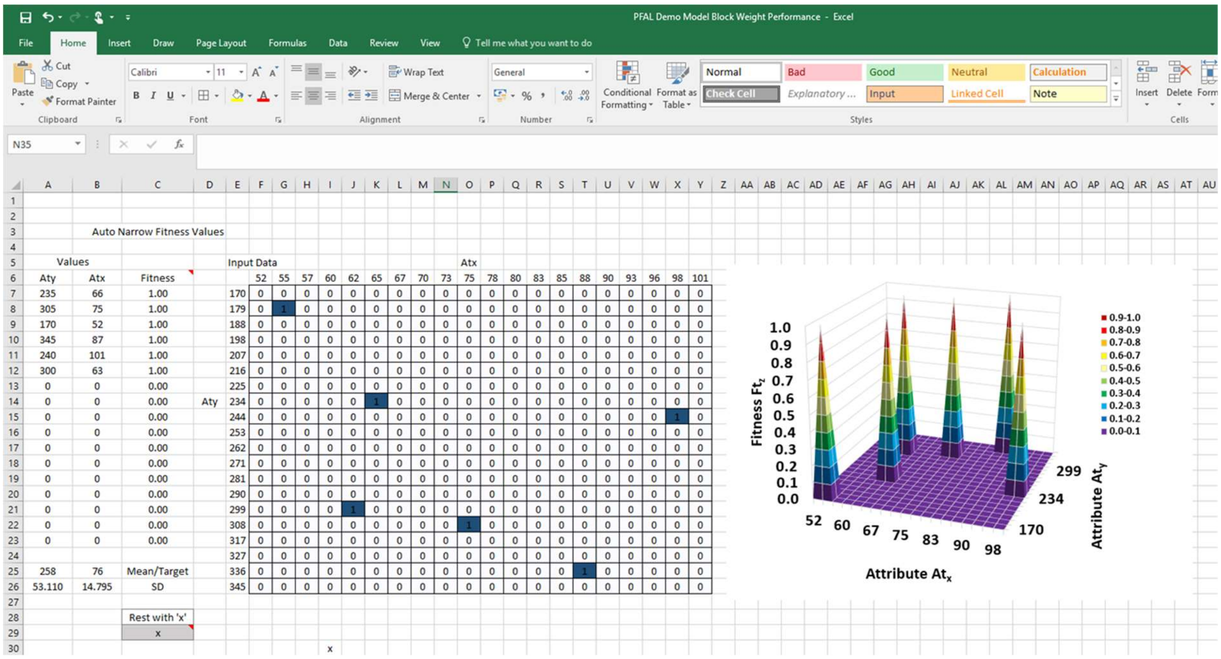

Figure 65 PFAL Start Point.

Stage 2: Fitness values are applied to the fixed points on the design landscape. Fitness values apply in the range zero (0.0) for infeasible locations on the landscape, to unity (1.0) for areas of known optimal peaks. Some knowledge of the character of the landscape is required in setting these fitness values, such as whether the landscape is expected to represent a Pareto frontier or an unconstrained peak. Fitness values may be manually entered based on the designer's knowledge or relative fitness calculated by proximity to centralised locations in the sample points - see section below on Fitness Values selection. Anchor points, representing constrained areas of the landscape can be manually applied to the model as fixed points. These force the landscape to ground, so that infeasible zones can be properly modelled. Figure 66 shows the initial sparse data points mapped to the landscape as narrow peaks, with relative fitness values applied.

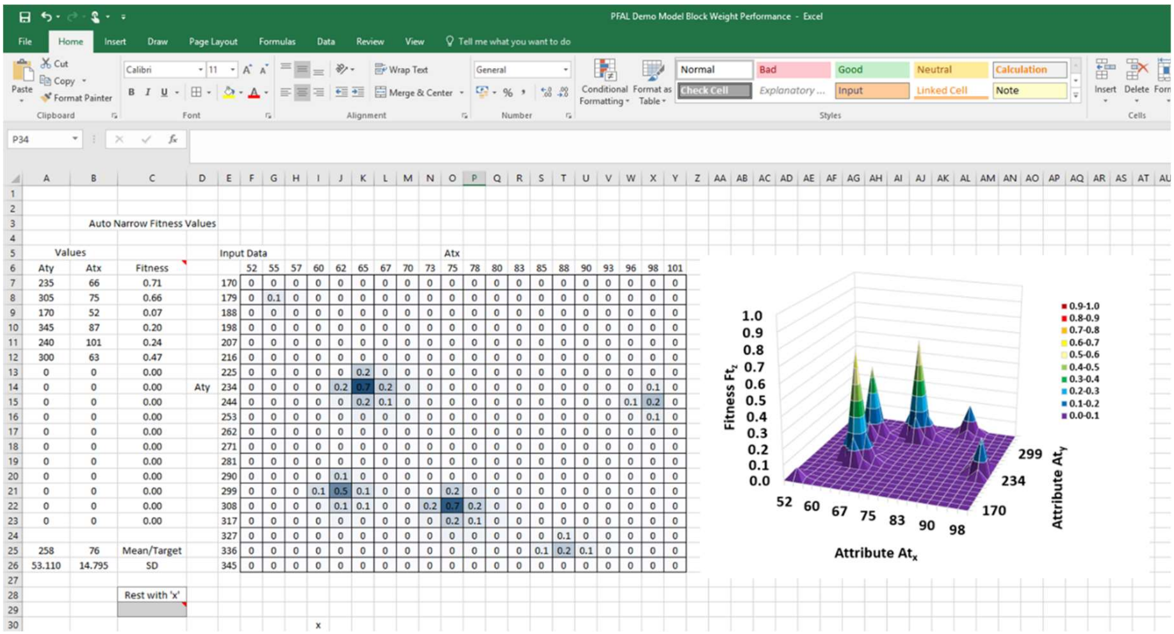

Figure 66 Initial Sparse Data Points.

Stage 3: The model is run with the required number of iterations for the smoothing algorithm to converge on a stable solution with no more adjustment in the landscape surface. Manual iterative calculation is set to allow self-referenced fields to recalculate, thus avoiding circular referencing in the modelling calculations. A setting of 1,000 iterations per run, with a maximum change of 1 allows control over the convergence process to be observed whilst ensuring that convergence occurs in a reasonable time. A number of runs (typically 20-30) are required before convergence occurs. Figure 67 shows the stages of convergence for a sample set of data to obtain the final adaptive landscape representation.

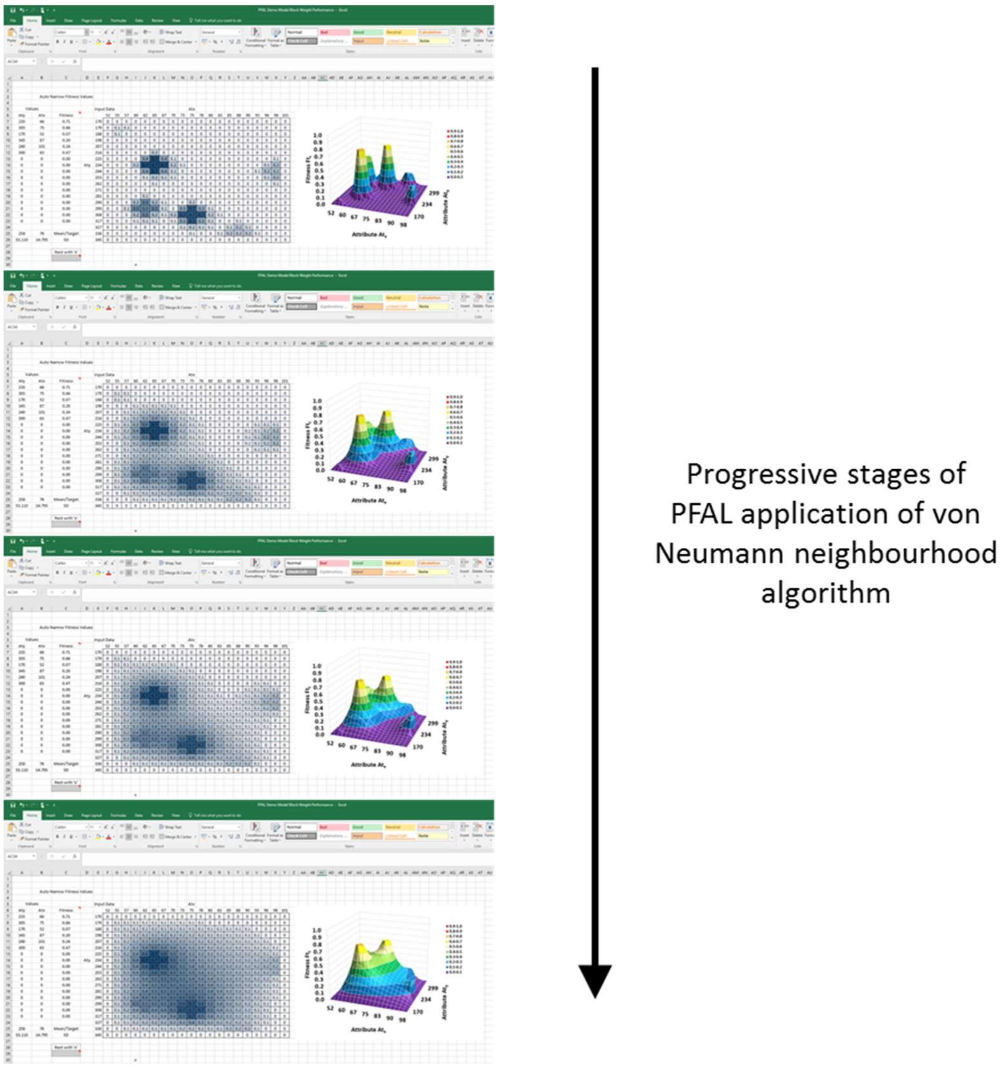

Figure 67 Stages of Convergence.

The adaptive landscape can be then interpreted using the generated surface to find alternative design space locations that may form the basis of new designs. The surface provides a clear visual representation for the designer of options and limitations in design values, that would be difficult to determine by numerical calculation means.

Modified Adaptive Landscapes

From the benchmark data, a plot of the attributes under investigation is thus generated. This shows the location and density of extant engines that have these attributes. Depending on the criteria being considered the optimal points may be a central position or a Pareto frontier (edge). The example in Figure 68 shows a Pareto frontier formed by a data set that approaches a desired target but is sensitive to exceeding that target. An example would be a design target for a crankshaft to have low weight. A low weight crankshaft has benefits of cost, material utilisation, package size and rotating component load and dynamics. However, alternative designs have limits of load carrying capability within the material properties available. Thus, lightening the crankshaft design has benefits up to the point of likely failure. Figure 68 illustrates the trade-off of mass reduction versus load capability showing how a Pareto frontier can form.

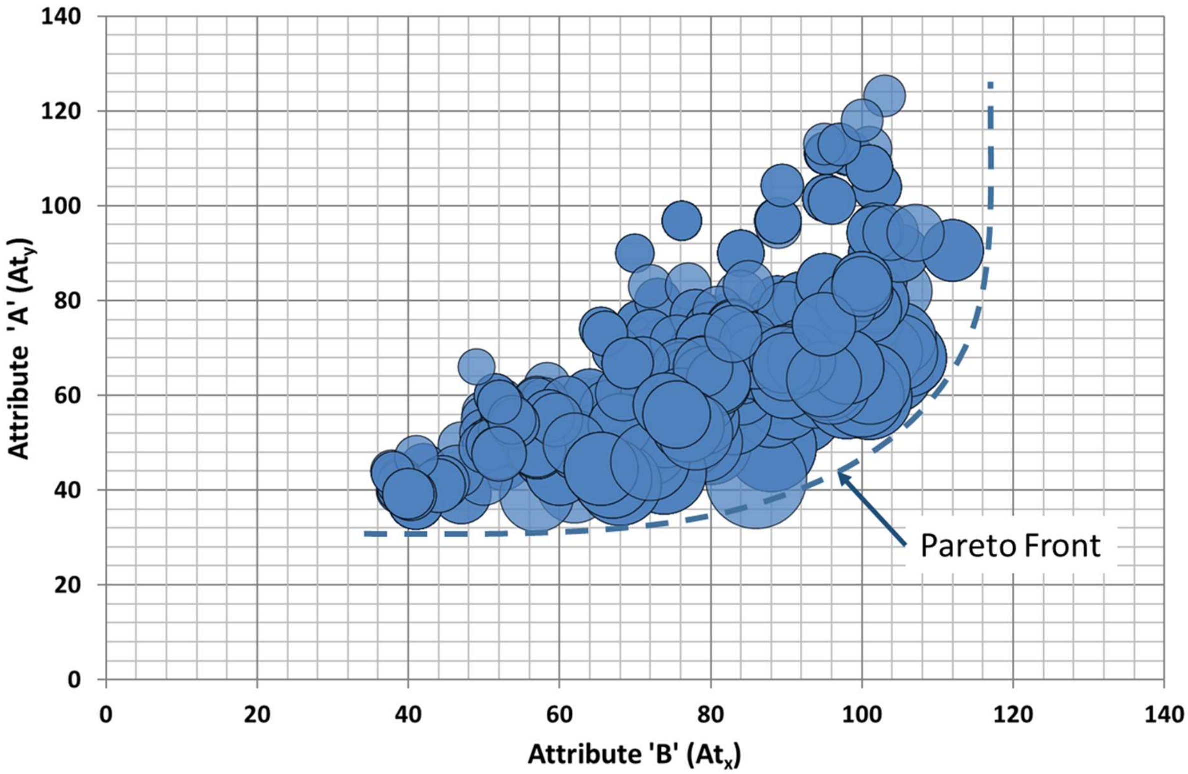

Figure 68 Pareto Frontier Design trade off.

The most desirable combinations of attribute are immediately behind the frontier and would form a ‘plateau of goodness’ on the adaptive surface. This is a zone of near equivalent optimal position. Although the Pareto Frontier itself represents an idealised condition the closer a selected attribute pair are to the frontier, the less room they have for change (moving on the landscape surface) before they encounter an infeasible zone. As values move away from the plateau they may still be viable but with diminishing fitness the further they move away. There will also be a zone of the map that is considered infeasible for this particular engine design. This infeasible region is identified in Figure 69 as a flooded plane on the landscape. The flooded plane is described by all areas of the landscape below a set value of fitness i.e. those values of fitness considered infeasible as design options.

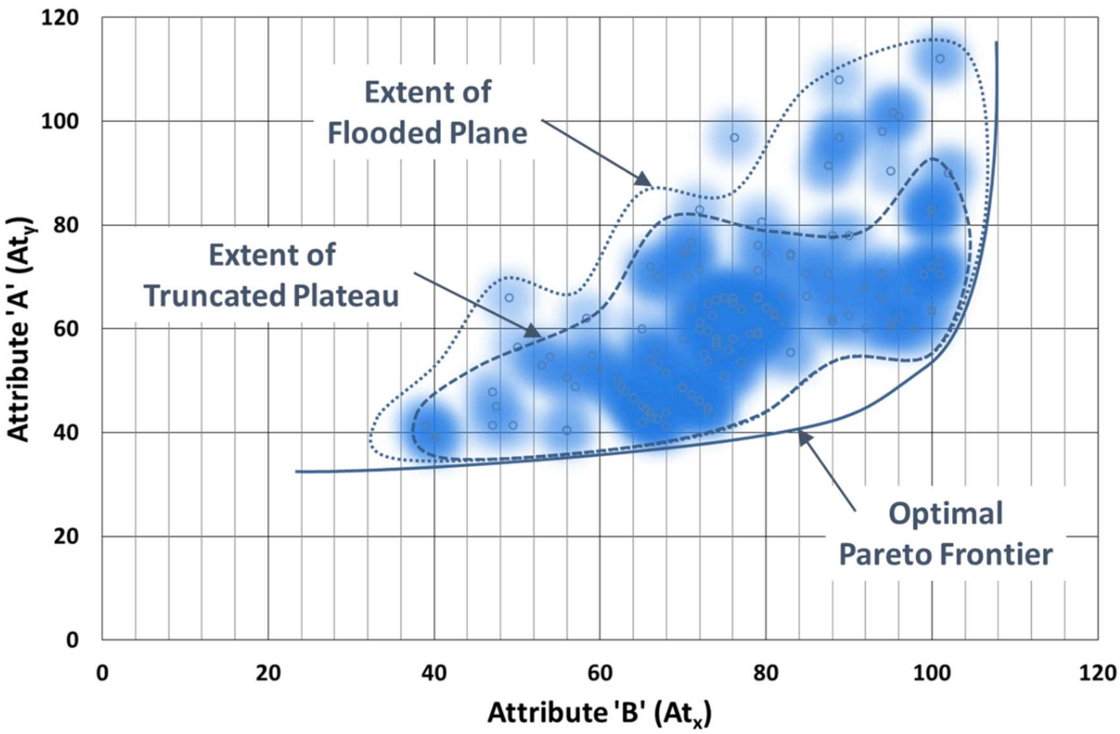

Figure 69 Pareto Frontier.

An example of an attribute map with sparse data is shown in Figure 70. This is for engine bore size against engine packaging box size for selected benchmark data. This shows the three zones discussed above. A target optimal Pareto front is shown, with known feasible designs located close to the optimal edge. Other feasible, but less optimal designs are indicated on the design space, with the limits of feasible designs shown by the extent of the flooded plane. This allows a visual representation of design feasibility that is rich in information and easy to explain to other stakeholders involved in the concept selection, such as marketing, manufacturing and senior management.

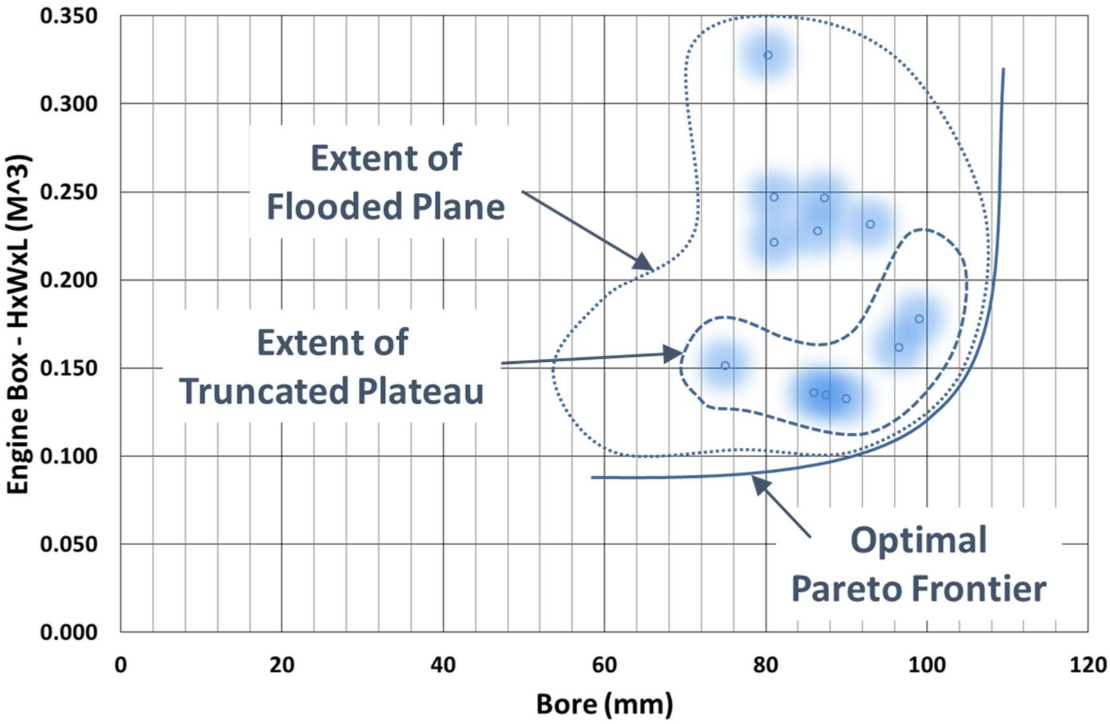

Figure 70 Sparse Data Map.

An attribute adaptive landscape is a 3D representation of a surface showing fitness of attribute pairs for a range of values. Traditional optimisation processes would use hill-climbing techniques to find peak values - see section 2.3 Application of Biological Models. To create geometry that is resilient to change and can accommodate varying conditions, the peaks are equalised at a point of satisfaction. This forms a plateau that truncates the peaks at a level of fitness that satisfices the target requirements for the design study. Figure 71 shows how this plateau plane intersects the adaptive surface.

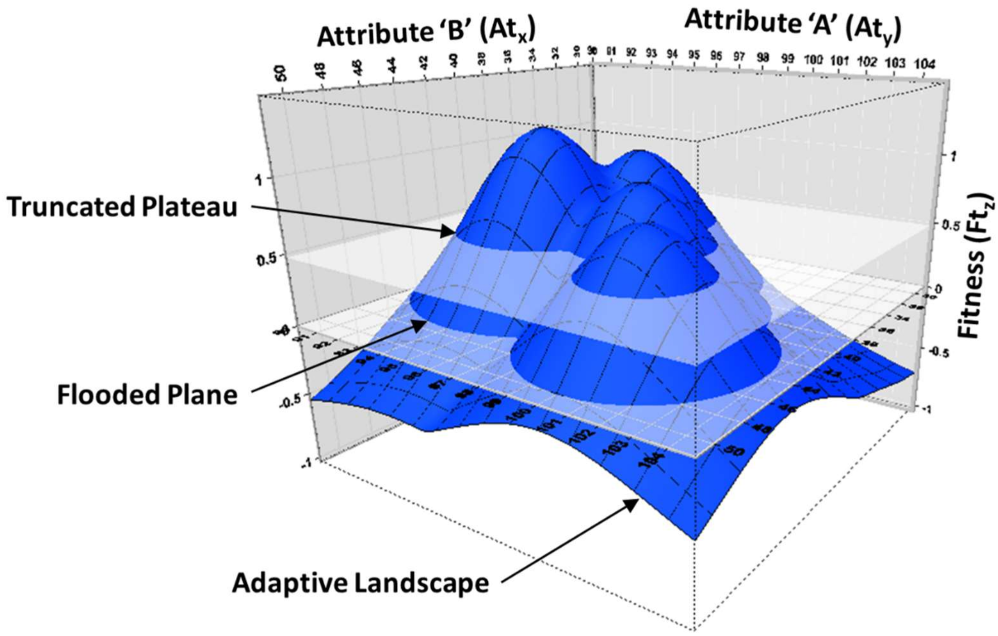

Figure 71 PFAL Description.

There is also a level of fitness value that would be unacceptable to the design objectives of the study. By 'flooding' the valleys of the adaptive landscape to this level any points on the surface below that value becomes an infeasible area and is discounted from consideration in the design. The intermediate zone between the plateau and flooded zones is feasible but less desirable than values on the truncated plateau, as they have reduced fitness utility.

An illustration of how this would apply to an adaptive surface generated from benchmark data is shown in Figures 72-74. A fitness surface is created from benchmark data points and filled-in using the von Neumann algorithm. This indicates peaks of fitness that are desirable locations for attribute selection.

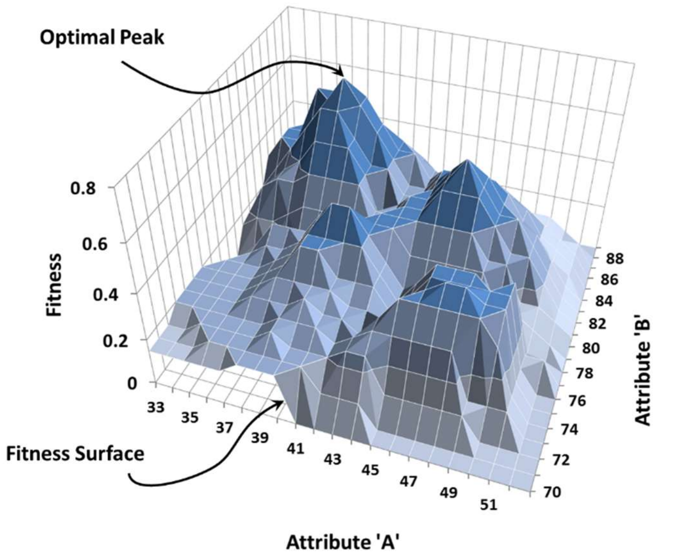

Figure 72 Full Adaptive Surface.

A plateau is applied to the data, which shows the extent of an acceptable, satisficing zone. This indicates that anywhere on this zone should satisfice the requirements of the engine design and therefore provides more flexibility in choice to trade-off against other requirements, than fixing on a peak value. This helps avoid the design selection becoming fixated on an optimal peak to the detriment of attribute selection for other factors.

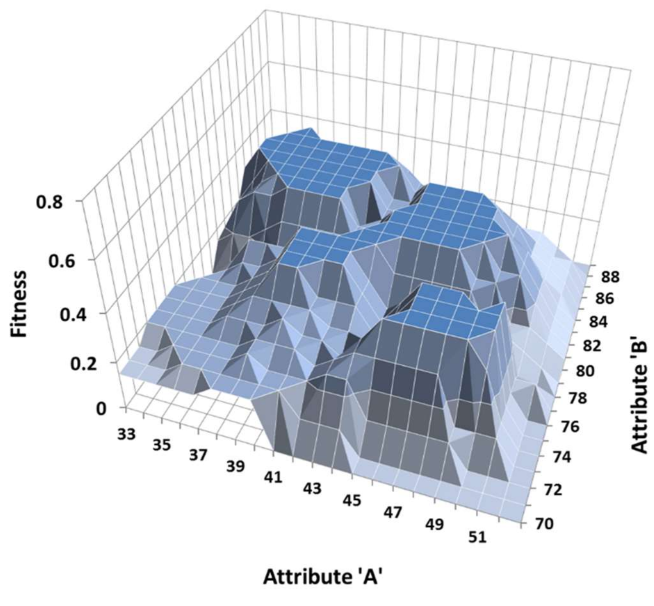

Figure 73 Plateau Plane Adaptive Surface.

A flooded plane is then applied to the model to clearly identify those areas of the adaptive model that are considered infeasible. As well as defining zones of the map that should not be explored, it sets the lower bound to the intermediate zone between the plateau and flooded plane (PFAL). The intermediate zone defines an area that is less desirable as it has less than satisfactory fitness values, but is still feasible as compromised design point locations.

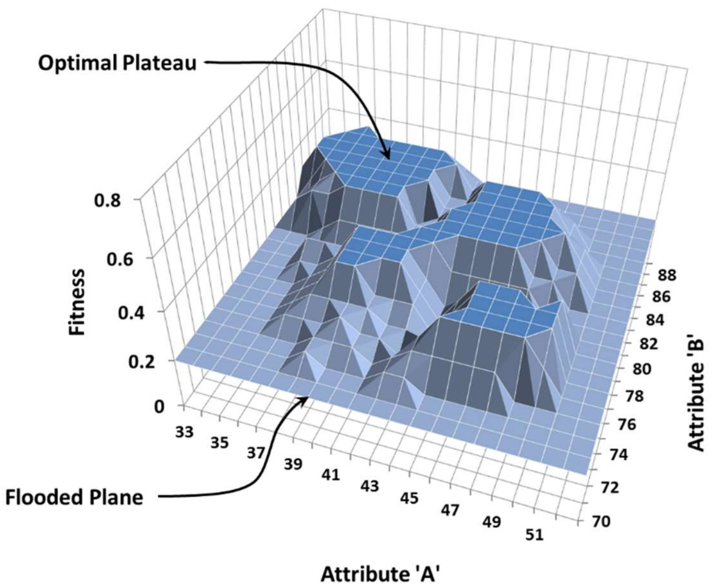

Figure 74 Plateau, Flooded Adaptive Surface (PFAL).

This staged process of constraining the adaptive landscape to defined zones identifies areas of interest to the designer. Figure 75 shows the PFAL method applied to a set of values that form a Pareto frontier. The infeasible zone is a sharp drop off on one side of the frontier, but with a more gradual slope, that forms part of an intermediate zone below the plateau, on the other side. The heuristic frontier is formed by heuristic values being generated from experience of known 'good points'. This represents the location of satisficing points that may not be optimal, but are near-optimal.

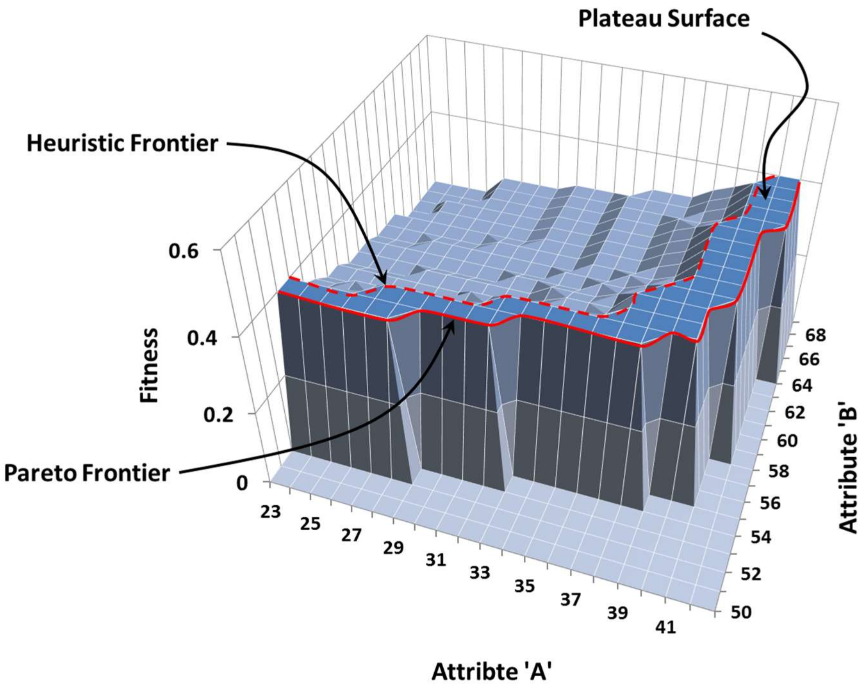

Figure 75 Pareto Frontier Adaptive Landscape.

A 2D view of the Pareto frontier example above is shown in Figure 76. This equates to a contour map of the adaptive landscape fitness values. The 3D view is useful in visualising relationships between points on the landscape surface, whereas the 2D view has greater utility in analysis and calculation as distances on the surface can be directly measured.

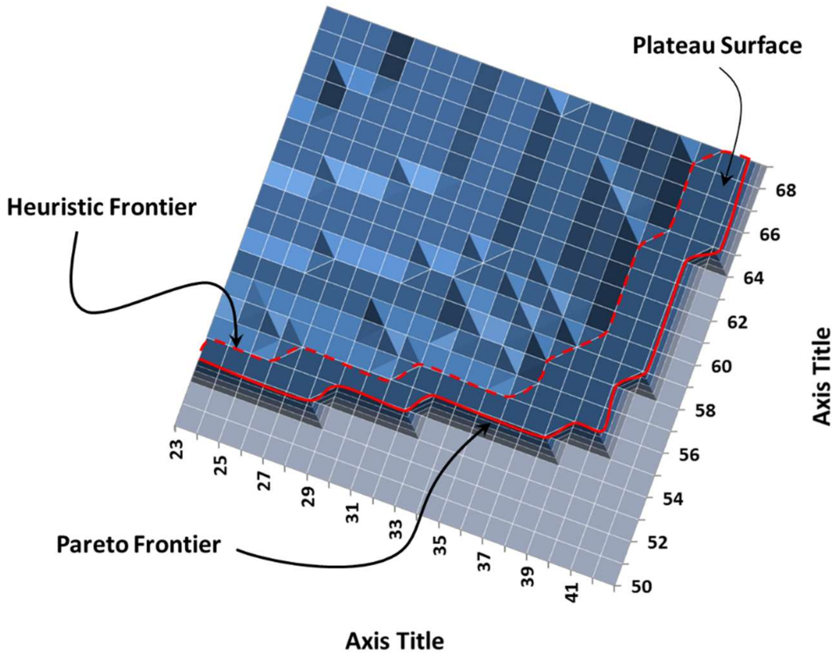

Figure 76 Pareto Frontier Contour Plot.

Peak fitness values may be skewed, but not strictly a Pareto frontier. Figure 77 shows an example that favours a particular location with a skew in fitness. This 'island' condition is formed when there may be an extended surface of relatively low fitness values.

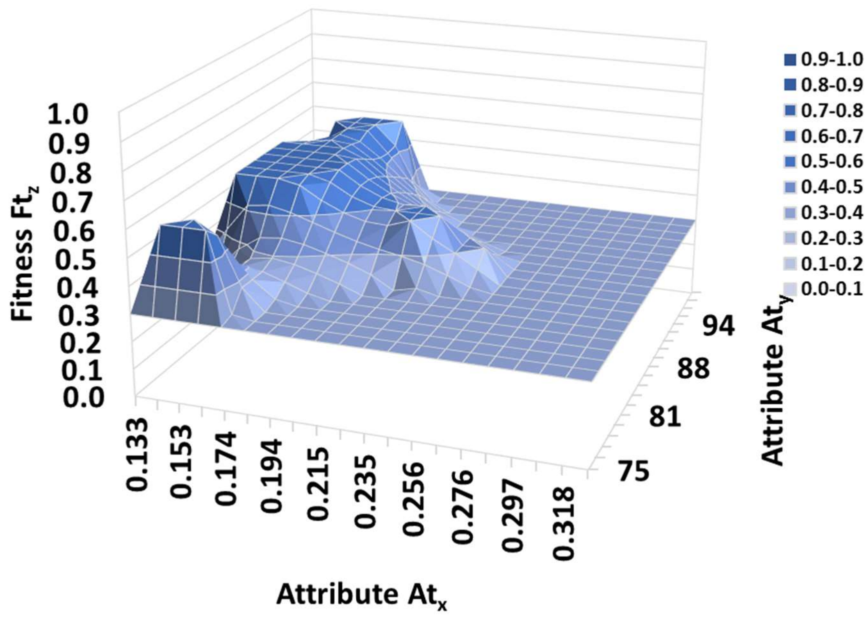

Figure 77 Skewed Optimal Peak Landscape.

The contour plot of the surface in Figure 78 shows how the low fitness values map out. This also provides a more accurate map of elevations of fitness value for analysis.

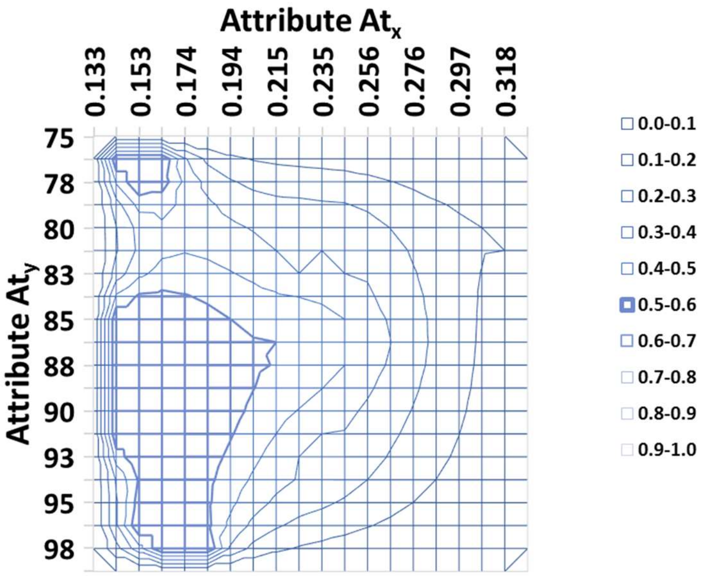

Figure 78 Skewed Peak Contour Plot.

Selection of Fitness Values

Fitness describes the ability of an entity to ‘fit’ or match its environment. This is not a measure of absolute ‘goodness’ or optimality. It is a relative term, comparing the fit of one entity’s performance in a given environment compared to that of another under the same conditions. As the conditions of the environment change, so will the fit of particular attributes to that environment.

The selection of fitness values are placed on a common scale for ease of comparison. Hence, if the attributes under consideration are engine length and bore size, and the fitness parameter being assessed is weight, the fitness scale is not measured in kg, but rather all values of weight are normalised to a scale between zero and unity (0-1), with the lowest weight being 1.0 (most desirable). This allows us to see relative positions of performance against the attributes under consideration.

The assignment of fitness values may sometimes be arbitrary. If the fitness axis (At_z) is non-dimensional, say because it represents an arbitrary preference, then the fitness values may be assigned by the concept designer from past experience of preferential designs or on the basis of judgement using guiding heuristics. This may be done when a combination of higher order parameters is being assessed collectively for the fitness parameter. For example, in assessing bore/stroke trade-offs the concept designer may have a mental model of a combined fitness attribute for At_z, such as overall preference for emissions, fuel economy and engine performance.

As much as this process lacks rigour and repeatability, it is not untypical of the kinds of subjective thought processes brought to bear by designers as they go through the concept generation and evaluation process.

In order to provide a more structured approach to assigning fitness values, a centralising theorem is used to calculate values. This process takes the value of each ordinate being considered and compares its value to the mean and standard deviation of values in the range for that attribute. The resulting fitness values for the attribute pair is a reflection of the relative position of both constituents to their range population.

The formula used is:

$$\frac{e^{-\left(\frac{(At_x - At_{\bar{x}})^2}{\sigma_x} + \frac{(At_y - At_{\bar{y}})^2}{\sigma_y}\right)}}{2}$$

Equation 1

This ensures that there is a consistent process used for the distributions of fitness across a landscape. The closer the benchmark or initial point is to a central value for the set of points, the higher the fitness value attributed to that point. This process works well for ‘islands’ of points that do not require modification by imposition of Pareto fronts or other constraining limits. If modification is required, this can be applied to the fitness landscape subsequent to fitness values being applied.

Norton-Bass Adoption Curve

The Bass model for the diffusion of technologies or products within a market was first proposed by Professor Frank Bass of Purdue University as part of a paper on modelling market share and sales rates, and was further developed in his follow-on paper of 1969 concerning growth in consumer goods (Bass 1969, 1963). The now classic S shaped curve of the Bass model describes the initial take-up rate of a product by early adopters. The S, or logistic curve, in various forms has now become a standardised model for adoption and diffusion of designs (Kucharavy & De Guio 2015, Chambers, Mullick & Smith 1979). This includes application to new engines configurations in engine designs and technologies in the automotive sector (Zoepf & Heywood 2012, Walter, et al. 2010, Teotia, et al.1999). Alternative models for diffusion of technologies include the Gompertz and Logistic models and a variety of modifications to the classic Bass model (Valle & Furlan 2011, Chandrasekaran & Tellis 2007). Modified Bass models have been shown to be applicable to substitution purchases of durable consumer goods, such as cars (Mahajan & Muller 1996). Modelling of replacement strategies for product platforms under conditions of competition most closely replicates the environment where a purchaser of a vehicle looks to replace that vehicle infrequently (durable product) with a similar or competitor replacement (Kang, Hong & Huh 2012). These alternative diffusion models are all derived from the original Bass model with varying degrees of modification to account for influencing factors on purchase choice.

Bass models have agents known as 'innovators' and designated by the coefficient 'p'. They are the first to adopt a new innovation but are only a relatively small part of the overall potential market. Later adopters are influenced by the adoption patterns of the innovators. These adopters are referred to as 'imitators' and designated 'q' in the model. They demonstrate a similar S curve to the innovators, but delayed in time and of greater magnitude.

The Bass model has been widely used in market analysis and the planning of market penetration rates for new technologies (Nieto 1995). It is the most common way of modelling both product sales and also the evolutionary adoption of configurations and technology dissemination in an industry. Mom (2014) applies the evolution of automotive technologies showing how diffusion processes occur within an industry. Massiani & Gohs (2015) show how the Bass model has be applied specifically to automotive technologies, with Fine & Li (1987) discussing the relationship between technology choices, product lifecycles and flexibility in manufacturing with reference to the Bass model for lifecycle modelling.

The Bass curve is generated by modelling the interaction of rates on cumulative take-up between innovators and imitators. This is done using time period analysis, where 't' refers to convenient time periods, such as months post launch.

For t = 1, 2, 3...

$$F(t) = \frac{1 - e^{-(p+q)t}}{1 + \frac{q}{p} e^{-(p+q)t}}$$

$$f(t) = \begin{Bmatrix} F(t), & t = 1 \\ F(t) - F(t-1), & t > 1 \end{Bmatrix}$$

Equation 2

The three Bass Model parameters (coefficients) that define the Bass Model for a specific product are:

- M -- the potential market (the ultimate number of adopters),
- p -- coefficient of innovation and
- q -- coefficient of imitation.

The potential market, M, is considered to be fixed, although in reality this will be dynamic and change over time. The model is for initial adoption and does not consider re-adoption, replacement or updates. These would be modelled as separate, following Bass curves. Later modifications to the standardised Bass model do allow for multi-generational modelling (Norton & Bass 1987).

One issue with the Bass curve is that it assumes a rapid rise of adoption and then as the market for the product or innovation becomes saturated, adoption rates fall off in a gradual decay curve. Sales of many products, such as smart phones, computer PC models, white goods, etc., follow these kinds of curves. It fits seasonal or fashion products particularly well as they have a definite season. Similarly, it closely matches initial dispersion of new technologies or innovative products. It is less accurate in standardised form when considering replacement demand, where there may be a more constant level of demand due to ongoing adoption or purchase of products to satisfy a perpetual need for a product in use, such as always requiring transport. However, this can still be modelled with the modified Bass theory, assuming each purchase decision including replacement product, is a new adoption (Jiang & Jain 2012, Kahn 2006). This is realistic, as replacement purchase of engines and transportation will be sufficiently infrequent that they are likely to provide opportunities for consideration of a new technology or configuration and so can be modelled as a new adoption curve.

Modifications to the standardised Bass model have evolved to consider external influences on adoption rates, including incentives and competition (Liu, Klampfl & Tamor 2013, Lambkin & Day 1989). Initially developed to describe diffusion of a new technology, the Bass model has been extended to consider multi-generational products. This includes products that leap-frog in the manner of successive new models of product that come to market, for example, a new variant rather than a new technology (Redondo & Cagigas 2015, Norton & Bass 1987).

The generalised Norton-Bass model has been shown to cope well with multi-generational products that count purchases of product already made (Jiang & Jain 2012, Jeon 2010, Pae & Lehmann 2003). This replicates the situation with the introduction of a new variant of an engine family to market, over the production life of the product. Modified Norton-Bass models are therefore a good predictor of engine lifecycle modelling. This has been validated by modelling the Rover K series engine total production volumes over its production life - see section 4.3 Norton-Bass Models.

3.8 Retrospective Engine Lifecycle Analysis

Validation of the modified Norton-Bass model has been conducted using retrospective analysis of the lifecycle of engines in production. The duration of engine lifecycles and the expense of creating an engine configuration mean that it is not feasible to have multiple engine designs from one manufacturer tested in the marketplace at one time. In addition to the costs associated with variety of engine architectures, the strategy would reduce the economies of scale for the company's engine portfolio (Salvado, Forza, & Rungtusanatham 2002). Companies seek to reduce variety in product offerings whilst satisfying as many of the market niches as they can (Wan, Evers & Dresner 2012, Fisher & Ittner 1999). This presents a challenge in managing variety of product offerings whilst commonising dimensions, components and systems as much as feasible.

It is therefore not feasible for a single manufacturer to test the market for different designs using hardware options. The potential configurations of engine architectures must be evaluated using simulations of the market. In order to do this, models of likely take-up rates for engines were created using modified Norton-Bass models. A representative family of engines, with known production history can act as a proxy for the planned engine product. By modelling heuristic production life data, we can model the financial case for changes in investment strategy created by different change capacity scenarios drawn from adaptive landscapes. The Rover K series engine provided a suitable model for this analysis, as production data was available for the complete life span of the engine family, together with investment information and documented design configuration changes.

Each engine family has a unique production life, based on the particular constraints of the market conditions at the time it was in production, the fit of design to market needs, the change environment prevalent at the time and a host of other influencing factors. Even with the same starting conditions for an engine in terms of the segments of the market demand it is seeking to satisfy and the design philosophy of the designer laying out the concept architecture, the actual lifecycle changes over the production life of the engine could not be replicated exactly on separate occasions. What this means is that just because a particular design configuration has been successful in the last product family (or not) does not mean that will be repeated for the next generation of engines. This is because there are so many other factors that influence the success of an engine design. The designer should therefore be cautious in relying solely on retrospective analysis to validate models. However, it provides us with a reasonable fit of empirical data to the model, as shown in Figure 93.

3.9 Concluding Remarks on the Study Methodology

The development of a technique for engine concept design modelling needs to incorporate the parametric model approach using heuristics drawn from benchmark data. This is a commonly adopted approach in the design of engines' concepts (Dopson, Taitt & Sandford 1995). The period when an engine concept design is laid out is a relatively short period of a few weeks at the start of an engine program of optimisation that may last 3-4 years. It is also conducted relatively infrequently, as the product will be in service for 8-12 years and new engine concepts are only generated when needed. However, the consequences of the decisions taken during the concept generation stage have major, long lasting impacts on the business and so need to be made with care. Any modelling technique or design process must be able to work with sparse data and be easy to apply.

The modelling techniques adopted for this study were chosen to meet the following criteria:

- The models should be easy to adopt by concept designers with no specialist knowledge of data analysis or specialist software.
- The models should be adaptable to expanded development for future needs.
- The models should have a balance of fidelity and ease of calculation. This was done to improve modelling resolution time and also to ensure that the work concentrated on the process, rather that the analysis task itself.

The use of Microsoft Excel was determined early on in the project due to its ubiquity within the engineering field. As a general modelling tool, it is somewhat undervalued and has the capability of producing quite sophisticated models with high utility. Excel lends itself well to modelling cell automata due to its inherent cell structure. This allows data values to be assigned to cells, as they map to locations on the adaptive landscape. Calculations can be built directly into the cells to perform mathematical functions. Excel also allows for iterative calculation, so that cell values can be updated to replicate ‘generations’ of a cycle.

The use of adaptive landscapes intuitively fits the work process of concept designers. It provides a visual representation that is easy to interrogate and shows the potential effects of trade-offs in geometry and feature choices. Engine designers already have some familiarity with the concept of viewing variables to be traded-off on a 3D surface through performance maps used in engine calibrations. Fuel maps, engine control maps and other system level functional controls are often modelled as a series of 3D surfaces. Figure 79 shows one such map for assessing specific fuel consumption on an engine against power and speed (Frass 1948, 1943).

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Figure 79 Engine Fuel Consumption Map. Frass 1943.

A form of fitness curve can be seen in Figure 80 from Noguchi, et al. (1995), looking at frequency of throttle settings from real-world driving data. Time at these throttle settings might be used to evaluate design options that perform better at certain points for function or efficiency. Frequency could therefore be taken as fitness in this instance. It is easy to visualise how a surface might be fitted to these points.

Aston University

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Figure 80 Engine Speed/Load Map. Noguchi et al. 1995

The methodology section briefly described the approach taken to modelling the adaptive metaphor on to an engine concept design using sparse data. The methods used are aimed at satisfying the needs of concept designers. A series of interviews with practising engine concept designers were undertaken to better understand their requirements. A survey of practising engines engineers was also conducted to understand the key drivers for change in the engines industry.

The methodological approach to establishing a decision support tool has been presented. The next chapter will look at the results of this method being applied to an exemplar engine from the historical record. The advantage of using a retrospective analysis is that the lifecycle of the engine's development is known and it will facilitate a review of options through looking at different scenarios of product planning at the concept stage. The next chapter will go then on to discuss some of the aspects of applying adaptive landscapes that need to be considered for future work.

4.0 Findings and Discussion

The previous chapter presented a structured approach to understanding the process of engine concept design for engines and a method for generating 3D fitness landscapes in design space. This chapter presents the findings of applying the PFAL process to the Rover K series exemplar engine and validation of its benefits through analysis of investment strategy outcomes and verification by concept designers on its utility in assessing design configuration options.

4.1 Introduction to Key Findings

The previous chapter laid out the methodology to be used in assessing the efficacy of applying adaptive landscapes to early stage concept design. Building on the requirements of concept designer needs, a process approach has been proposed. This was applied to a sample case study, the Rover K Series engine. This chapter presents the results of that analysis.

The staged approach to applying the PFAL method to sparse data in a concept design is described. Examples are shown of how the landscape representation changes as the PFAL model is applied. The visual nature of the process allows the designer to see the impact of design decisions on selecting options for further consideration and analysis.

The chapter goes on to validate the model against a simplified return on investment calculation of investment options using data drawn from the Rover K Series engine program. The modified Norton-Bass model for product adoption is used to describe market response to changes in multiple generations of products. Two options are modelled, one with dedicated production equipment for an original design that subsequently needs to be updated and another with design flexibility built in at the concept stage through the use of the PFAL model.

Finally, the use of the PFAL process is verified by experienced engineers working on concept designs, for its suitability and ease of use. This shows the potential of the method for further application on future engine design work.

4.2 Modelling Adaptive Landscapes

The ideal representation of an adaptive landscape is a 3D surface generated from a sparse data set that has representative interpolation between know points. The adaptive surface is a representation of feasible design space. The known points are by definition, feasible, but do not indicate all possible parameter combinations. In design spaces that have relatively few current examples the available data may not fully represent what is possible. This is particularly true of parameter comparisons for new technologies or areas that have traditionally been under exploited. The concept designer must therefore use their expert knowledge, derived from first principles calculations, prior design experience, trends knowledge and benchmarking activity, to make reasoned estimates on feasible space.

Heuristics allow the designer to establish likely scenarios of success in evaluating options. This is done by the addition of ‘fill-in’ data points between known sparse data and constraints on the adaptive landscape in areas of known infeasible designs. Central to this process is the designer having a feel for the likely shape of any adaptive surface, based on the expected characteristics of the parameters under consideration. For example, it may be reasonable to expect that a surface may be an open form, equally likely to expand in any direction. An example of this is bore/stroke ratio versus engine capacity, which is not constrained by geometry or the physics of the systems involved. However, when considering bore/stroke ratio itself (B/S), depending on the application, the generally idealised ratio is slightly under square (0.85) for a balance of combustion performance, emissions, fuel economy and power output (Hoag 2006) - see section 2.2.6 Concept Design Process for a discussion on bore/stroke selection.

A high-performance race engine would have an ideal bore/stroke over square, being up to 1.5 for Formula 1 engines This is driven principally by a need for efficient engine breathing (valve area) and high speed (low reciprocating masses) in a high-performance application. A ship propulsion unit on the other hand, whose performance requirement is driven by steady state efficient operation and durability, will benefit from a long stroke engine with B/S of 0.4. Whatever the application dependent idealised peak of the landscape, the bore/stroke landscape shape will be a ridge along a linear line with consistent B/S, gently falling away on either side. Figure 81 shows a range of representative bore/strokes for different applications of engines related to their power density and loading.

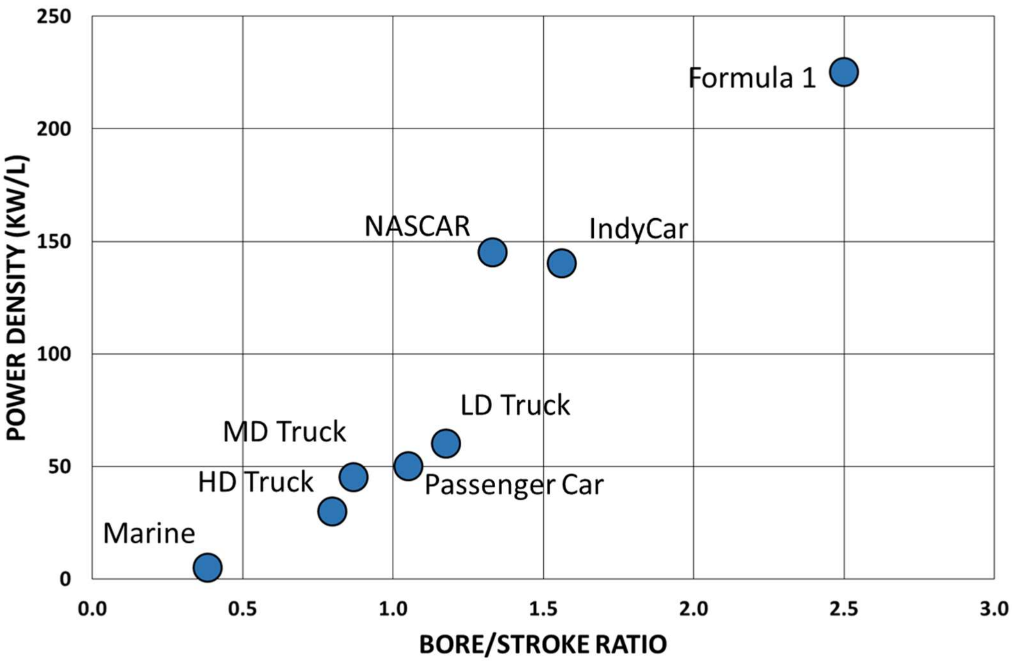

Figure 81 Bore/Stroke Selection for a Range of Engines Applications. Adapted from Herold 2012.

For other parameter combinations being considered such as B/S against fuel economy, there may be limiting factors that create a Pareto frontier. Named after the Italian engineer and economist, Vilfredo Pareto (1848-1923), who carried out pioneering work that showed a diminishing wealth distribution in society, it has come to characterise any relationship that shows a disproportionate (non-linear) diminishing trade-off between parameters in the form of a power law probability distribution (Arnold 2015). In engineering, Pareto frontiers are used to show an efficient front to a feasible design space. This indicates a 'front' to the data set that is optimal or of greatest efficiency. Outside the Pareto frontier is considered infeasible but inside the frontier, away from the front, whilst feasible, is less optimal. Figure 82 shows an attribute map of the kind that can regularly be found in technical papers on engine design (Hosoi, et al. 2001, Adachi, et al. 1998, Noguchi, et al. 1995, Doi, et al. 1994). The attributes of a range of benchmark competitor engines are indicated, together with a Pareto curve showing the fitness frontier for specific mass (kg/litre) against displacement. The chart also indicates some characteristic islands of fitness for engine block materials - iron and aluminium - showing a more detailed breakdown of assessment for comparison. The Toyota range of engines outside the frontier is intended to show their relatively high performance for this aspect of engine design. As they are extant engines they should strictly speaking form part of the frontier, albeit at the leading edge.

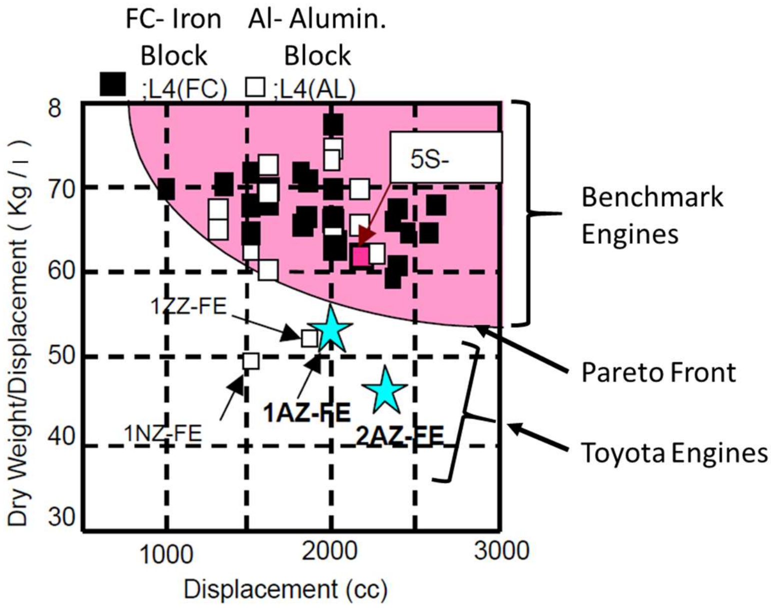

Figure 82 Specific Engine Weight. Adapted from Hosoi, et al. 2001.

It is therefore possible for the concept designer, knowing the expected design space profile, to use a combination of fixed data points from a sparse data set constrained by known infeasible anchor points to create an interpolated surface using a smoothing algorithm to fill-in the missing data set.

There are a large number of possible smoothing algorithm designs that could be used to interpolate between known points. A full evaluation of smoothing algorithm options is beyond the scope of this study. A simple averaging interpolation algorithm based on the von Neumann neighbour theory developed for cellular automata (Taffoli & Margolus 1987), has been used for modelling in this study. This smoothing algorithm was chosen for its ability to quickly converge on solutions and for it being amenable to incorporating the algorithm within a cellular automata environment

(Excel) without the need for specialist software. This approach also has the advantage of allowing assessment of the influence of dominant fixed points in generating a surface (Jones 1995). For this reason, the sparse data sets have been used without modification.

The approach of using a cellular automata model in Excel with the von Neumann smoothing algorithm was validated against proprietary surface modelling software codes (XLStat & NCSS) to test its accuracy for use in concept design modelling. A trial sparse data set of four points was used to create Figure 83. The adaptive surface was created using a 3D surface generation algorithm built within NCSS analysis software. Fitness values were attributed to the data points as an indication of optimal solution spaces. It can be seen from the figure that two dominant peaks are represented. The surface was constrained to zero fitness at the surface edges to represent infeasible zones - these are anchor points on the surface to create a viable landscape. The study aimed to replicate the idealised surface representation generated by specialist software, by using a simplified model that could be built into ubiquitous software tools (Excel).

The Excel based model was able to generate a surface using a simple averaging algorithm that was a near match for the idealised surface. Figure 83 shows the simplified surface model generated (SSM). The dominant peaks and the relationship between sparse data information is clearly replicated in both models. The decay rate from the peaks is less well matched but adequate for the purposes of concept design space understanding, as the intent of the adaptive landscape is to show form and magnitude - acting as a visual guide to design decisions, rather than an exact calculation. Detailed specific analysis on any chosen design point to validate the design choices made using the adaptive landscape will come at a later stage of the design process when there is greater definition of geometry. The designer is looking for relationships between points and the overall shape of the landscape surface in order to make appropriate configuration choices and design trade-offs at this early stage. Adaptive landscape modelling is essentially a visualisation tool and is not being used for quantitative analysis which would come later in the product development process when detail design analysis is conducted to refine and optimise the selected architecture.

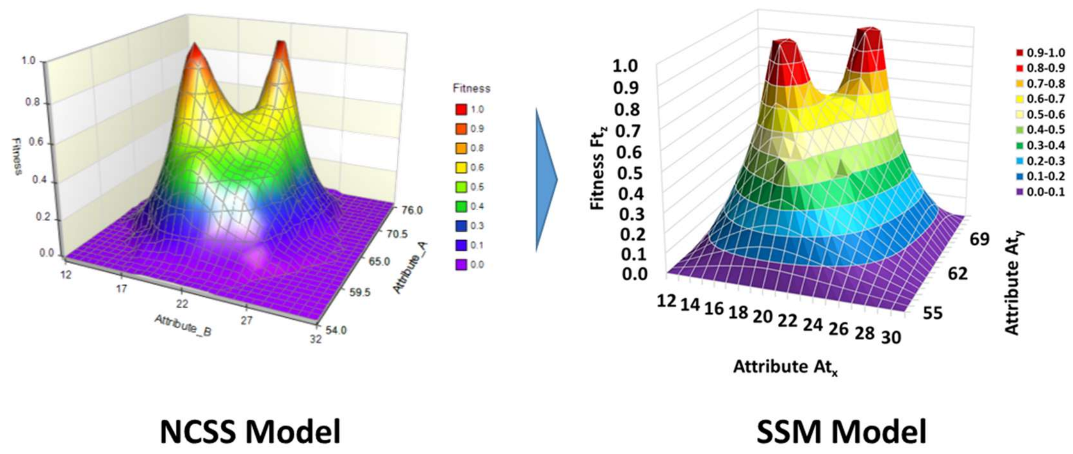

Figure 83 Surface Model Comparison.

The trial adaptive landscape surface was then adjusted by applying a plateau truncating function at fitness value of 0.5. This constrained the dominant data points to an optimal plateau, which can be seen in figure 84b. The fitness value of the peak indicates the minimal acceptable fitness across the peaks. By setting this value to an acceptance level it broadens out the optimal feasible zone. This shows the parameter plasticity that can be achieved by this geometry/factor selection.

The next step is to consider the infeasible zone of the adaptive surface (Figure 84c). This is the flooded part of the landscape which is considered by the designer to be so sub-optimal in parameter trade-offs that it needs to be explicitly discarded from the evaluation. The flooding level is applied to the plateaued surface at fitness value 0.2 to provide a completed feasible landscape for use by the concept designer. The three zones are now evident;

- An optimal plateau on constant minimal fitness 0.5
- A feasible surface zone of diminishing fitness away from the plateau between fitness 0.2-0.5
- A flooded plane of unacceptable fitness below fitness 0.2

A further refinement of the surface is to simplify the landscape to remove some of the nuance of the sub-optimal zone. This allows intermediate plateaus to emerge for consideration in designs that require resilience to change but when considered with other factors, may need to be moved away from an optimal plateau (Figure 84d).

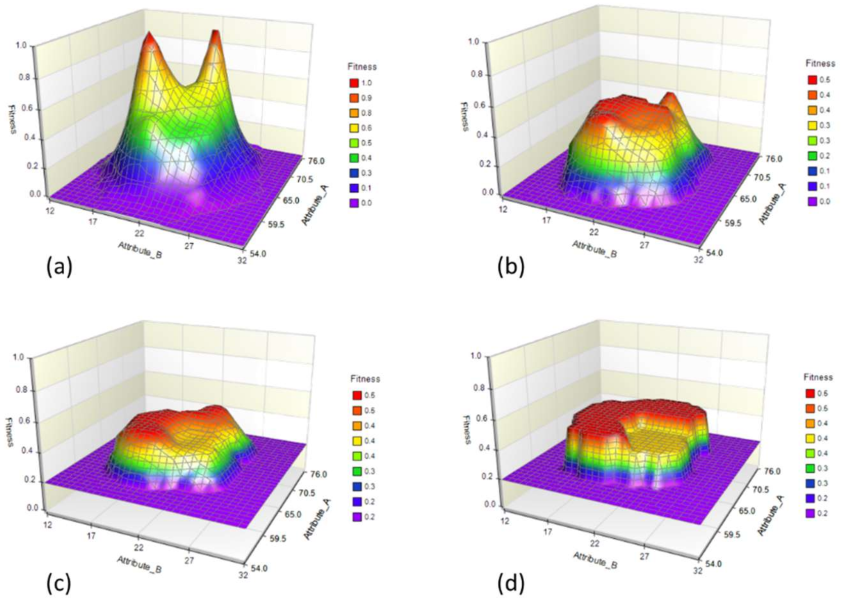

Figure 84 Surface Models NCSS.

The adaptive landscape surfaces shown in Figure 84 were generated using specialist smoothing algorithms within the NCSS code. The simplified surface model (SSM) was applied to the sparse data points to replicate the NCSS generated surfaces. These were used as an evaluation baseline for visual comparison to the corresponding surfaces generated in the Excel model.

Figure 85 shows the landscapes generated in both software packages for direct comparison. Various stages of applying the PFAL modelling process can be compared between the NCSS and SSM surfaces. Figure 85a is the unmodified surface created from the four sparse data points and using a simple averaging interpolation algorithm. Figure 85b has fitness values above 0.5 capped to that limit, thus generating a plateau of adaptive space. Figure 85c floods the generated landscape to 0.2 to represent the infeasible zone. The final stage is to apply a combining algorithm to the sub-optimal surface to a fitness value of 0.4, to clarify the position of intermediate adaptive plateau (Figure 85d).

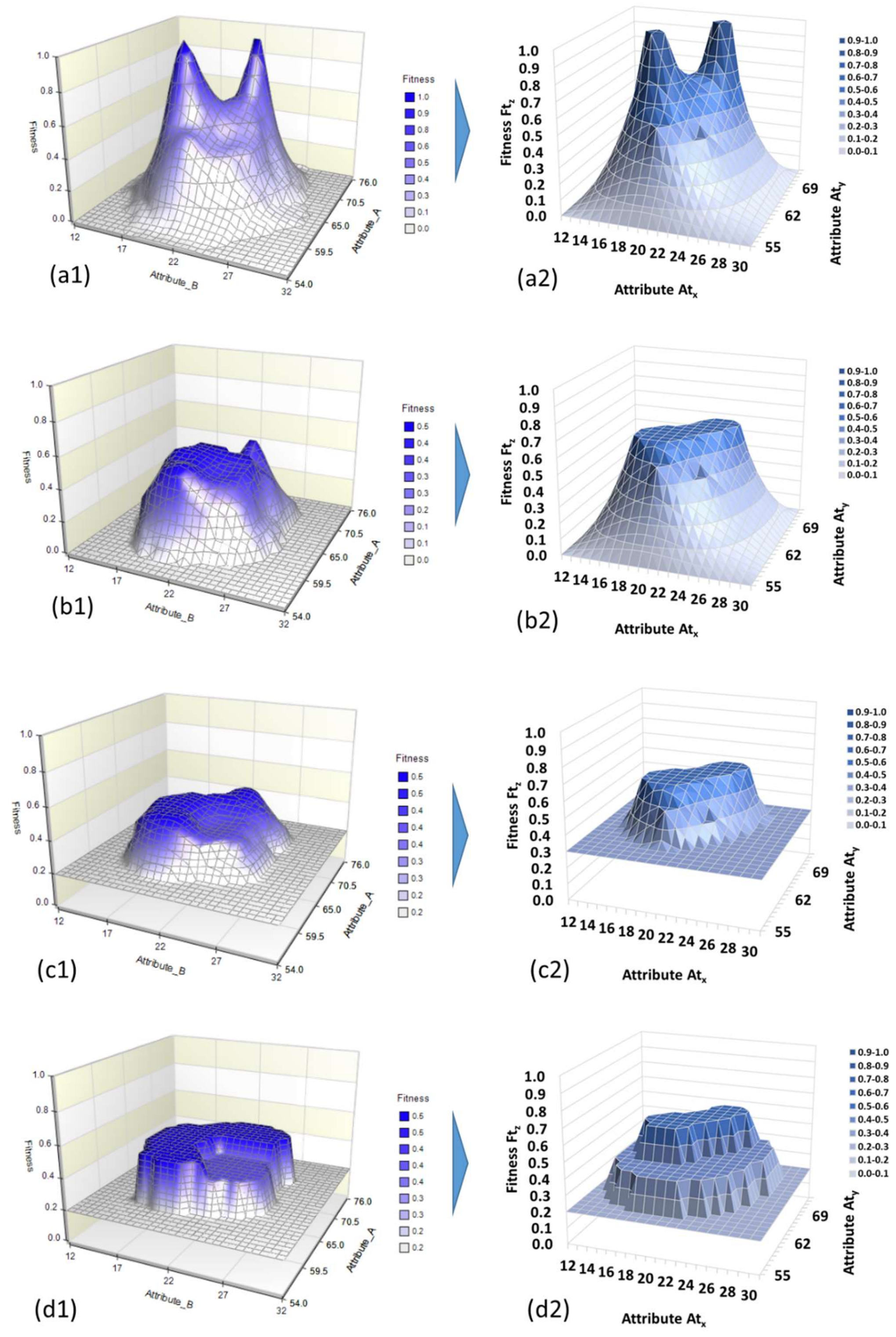

Figure 85 NCSS/SSM Comparison.

4.2.1 Example Application

A set of 17 benchmark data points from a database of engines for bore and stroke dimensions were used to create an adaptive simplified surface model (SSM). No attempt was made to modify or fill-in the points based on designer experience, so that an evaluation could be made on fixed data point input alone. Fitness values were applied based on highest values given to a constant bore/stroke ratio of 1.0 (square). Diminishing fitness values were applied away from the optimal ridge. A 20x20 resolution grid was used to model the surface. Figure 86 shows the grid and data points entered as a starting point, with their calculated fitness values, after the algorithm has run. The interpolated fitness values are also shown on the grid together with the corresponding 3D representation generated.

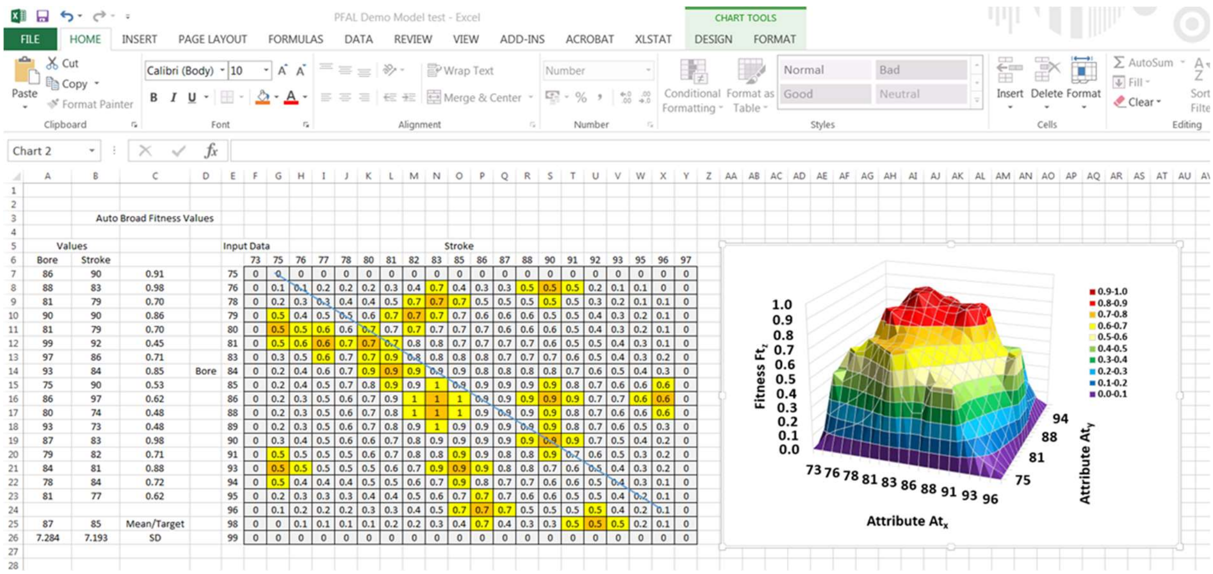

Figure 86 Input Grid.

Figure 87 shows 3D plots of the fitness surface with the progressive stages of performing the PFAL process: (a) full surface model with SSM algorithm applied, (b) a plateau fitness value of 0.6 applied, (c) plateau value of 0.6 combined with flooded plane of 0.3 fitness, (d) Plateau 0.6, flooding 0.3 and intermediate surface values 0.4. The higher values of fitness are indicated by darker colours with the flooded plane being the lightest colour.

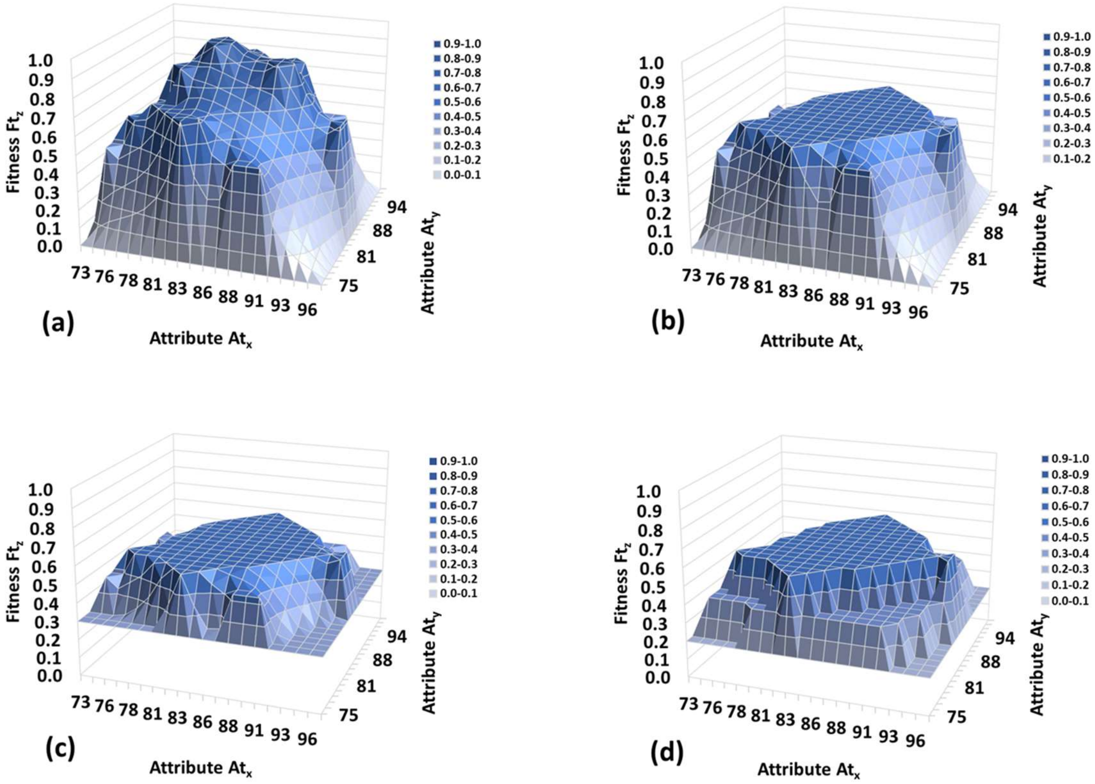

Figure 87 Bore/Stroke PFAL.

A contour plot of the adaptive landscape was generated to smooth out the lines around each fitness level to better represent a full 3D surface. Figure 88 shows the corresponding contour plots of fitness respectively for (a) full surface, (b) Plateau surface, (c) Plateau, flooded surface, and (d) simplified plateau, flooded surface. All fitness values and cut-off points are as shown for Figure 87. The benefit of a contour plot is that it allows a clearer view of all sides of the landscape and direct measurement of relative values in a similar manner to how the contours of a geographic map aid calculation of distance and elevation to locate points in the landscape more accurately.

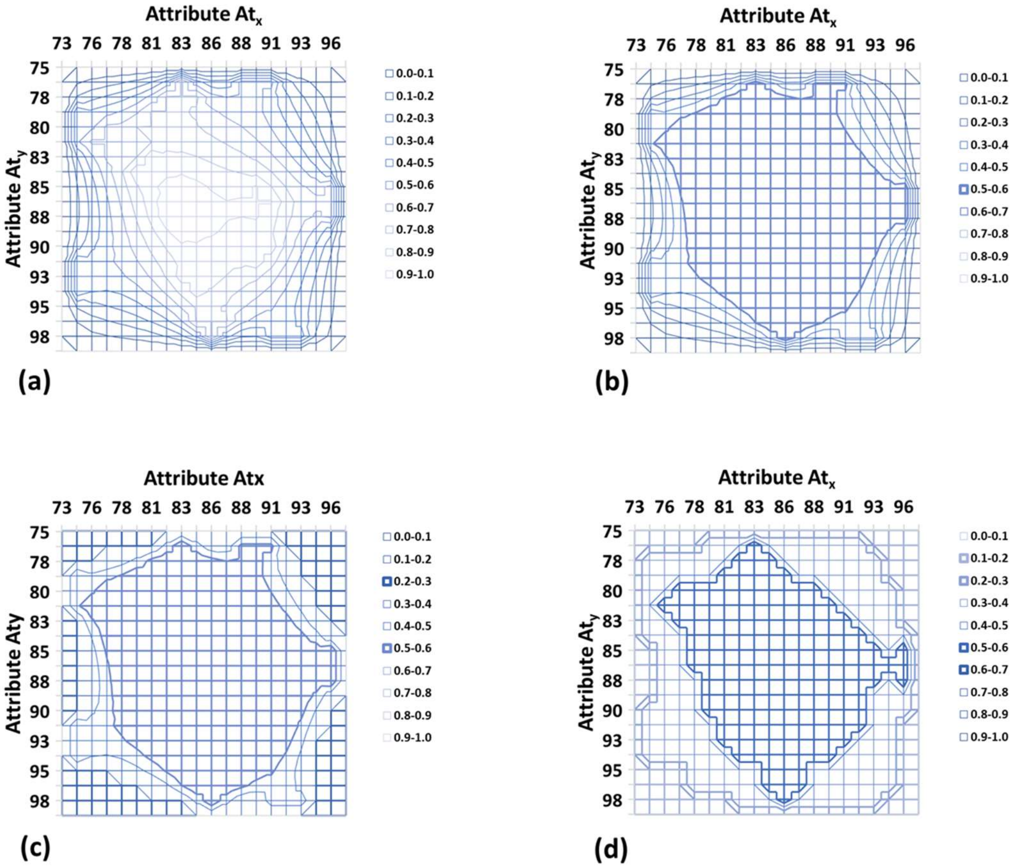

Figure 88 Bore/Stroke PFAL Contour.

A heat-map view of the surfaces also can be generated to gain an overall perspective of the areas of high fitness (Figure 89). This view of the data is useful in quickly assessing islands of fitness on a map without the need for detailed interpretation of contours. The shading of the map can be altered with relative ease to highlight fitness levels over a set value for evaluation. It can be seen that the stages of applying the PFAL process to the previous visualisations have been replicated here in the same order. Figure 89d therefore shows a plateau at 0.6 fitness, a flooded plane at 0.3 and an intermediate plateau at 0.4. The three plateau areas can more clearly be seen on the map than a pure contour map.

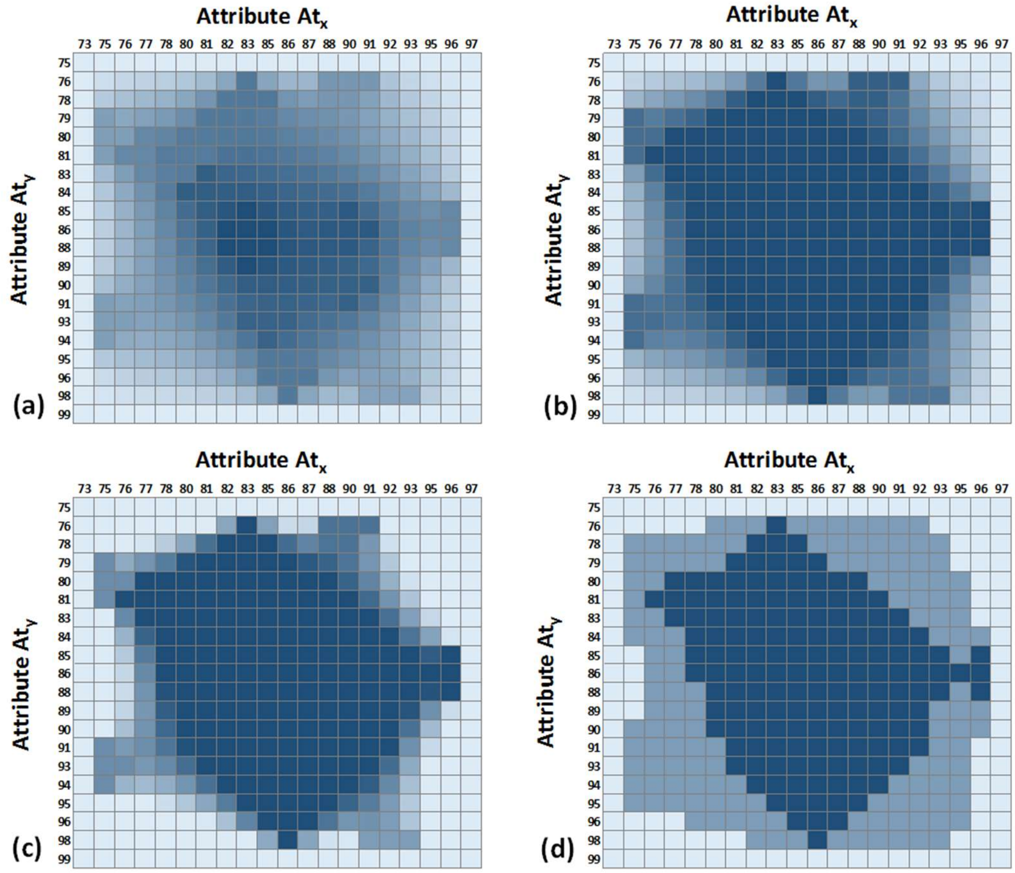

Figure 89 Bore/Stroke PFAL Heat Map.

The range of visualisation options available provides a view of the data to suit different needs. Communicating the sense of the shape of the adaptive landscape is best done with the full 3D surface. This would be useful in discussions amongst concept design stakeholders regarding optimisation of the parameter selection and plasticity to change. The full 3D surface also gives the designer a feel for the degree of flexibility in parameter selection. The contour plot allows for more detailed calculation of trade-offs and risks in selection of particular points on the landscape for parameter selection. The heat map is an extension of the contour map that combines the relative geometric fidelity of the contour map with the visualisation aspects of the 3D surface to highlight relative fitness values.

4.2.2 Sparse Points Mapping

As an example of how the PFAL process might be applied to sparse points, the same fitness limit values used on the 17-point bore/stroke example above have been applied to the four point data set used to correlate with the NCSS model (Figure 83).

Using sparse data of only four points is representative of measured detail data from a competitor engine benchmarking activity that might typically be carried out at the start of evaluating the need for a new engine program.

Figure 90 shows how with only four points a reasonable surface can be obtained, from a complete surface through to a much simplified, plateau segments representation. The surface produced provides rich information on feasible zones. With only limited data, care needs to be taken to ensure that all surface zones indicated are in fact feasible. This would be validated through subsequent detail analysis of specific selected locations on the adaptive map at a later stage of the design process The map's purpose is therefore limited to identifying areas of opportunity and risk.

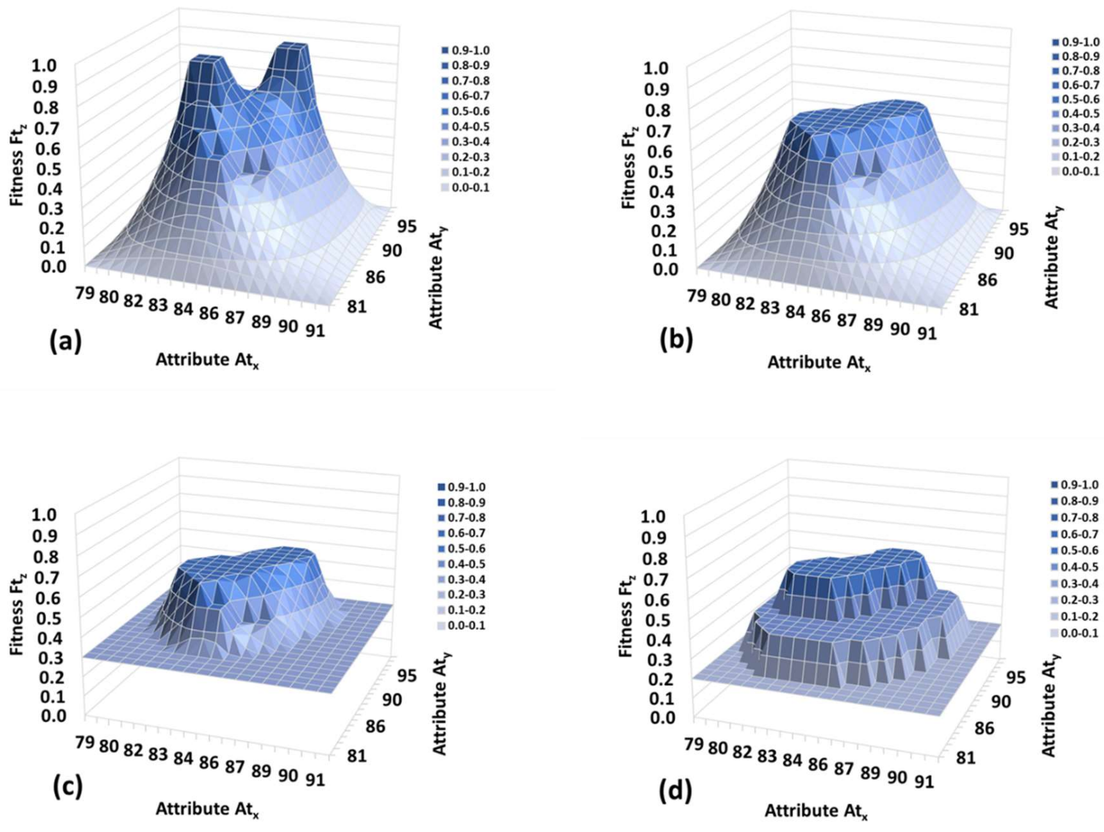

Figure 90 Four Point PFAL.

Viewing this data as contour plots (Figure 91), shows a very clear representation of fitness island formation and the boundaries to fitness zones. This shows groupings of attributes that may be relevant to parameter selection, such as options for materials or design features e.g. cylinder block material, pressure-charging or other step change attributes. Having relatively few data points gives some sharp differentiation between fitness zones that should aid evaluation of these alternatives.

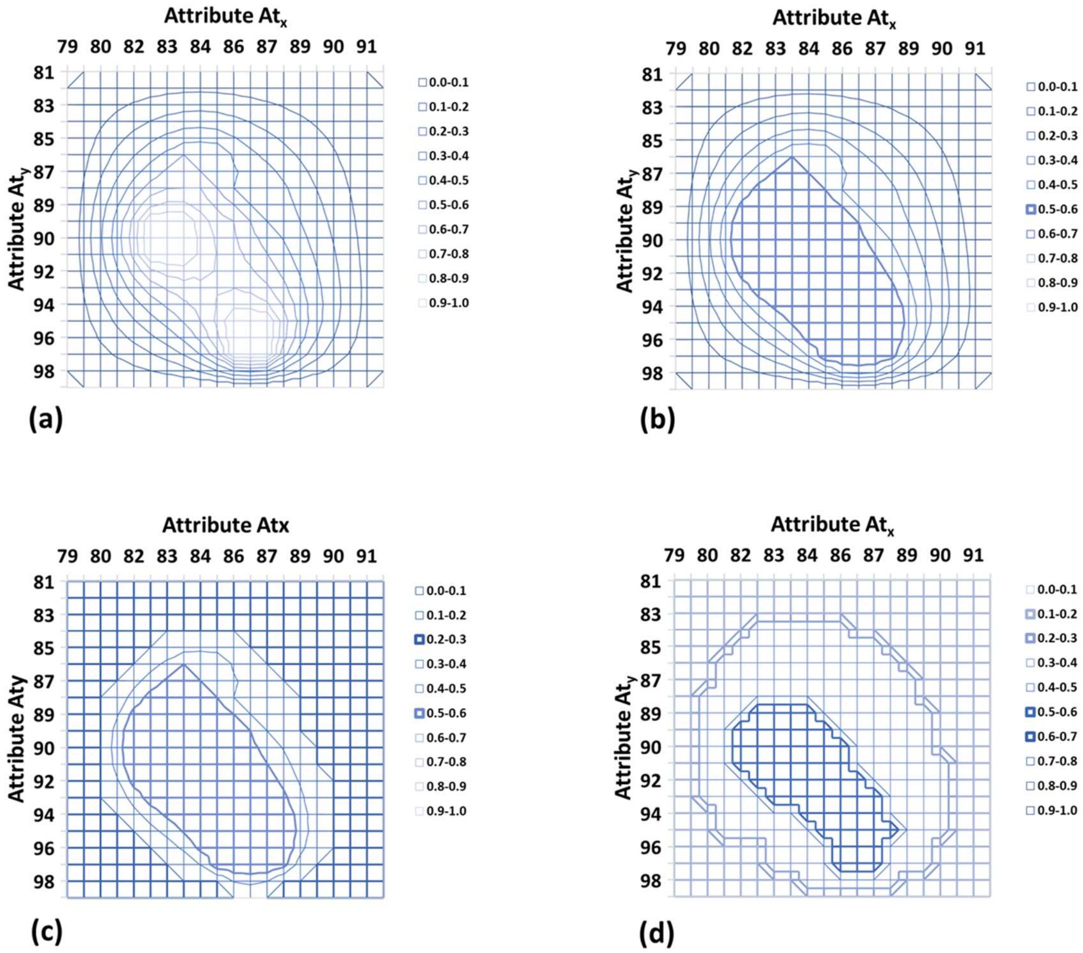

Figure 91 Four Point PFAL Contour Map.

The heat map for the four-point data set gives sharply defined boundaries that can be tailored for the requirements of the designer's evaluation needs. This gives a view of the full surface, as 2D surface geometry does not obscure any part of the landscape. It retains the fitness value emphasis of the 3D surface, but in flat form that allows clearer relative position analysis of comparative points on the adaptive landscape.

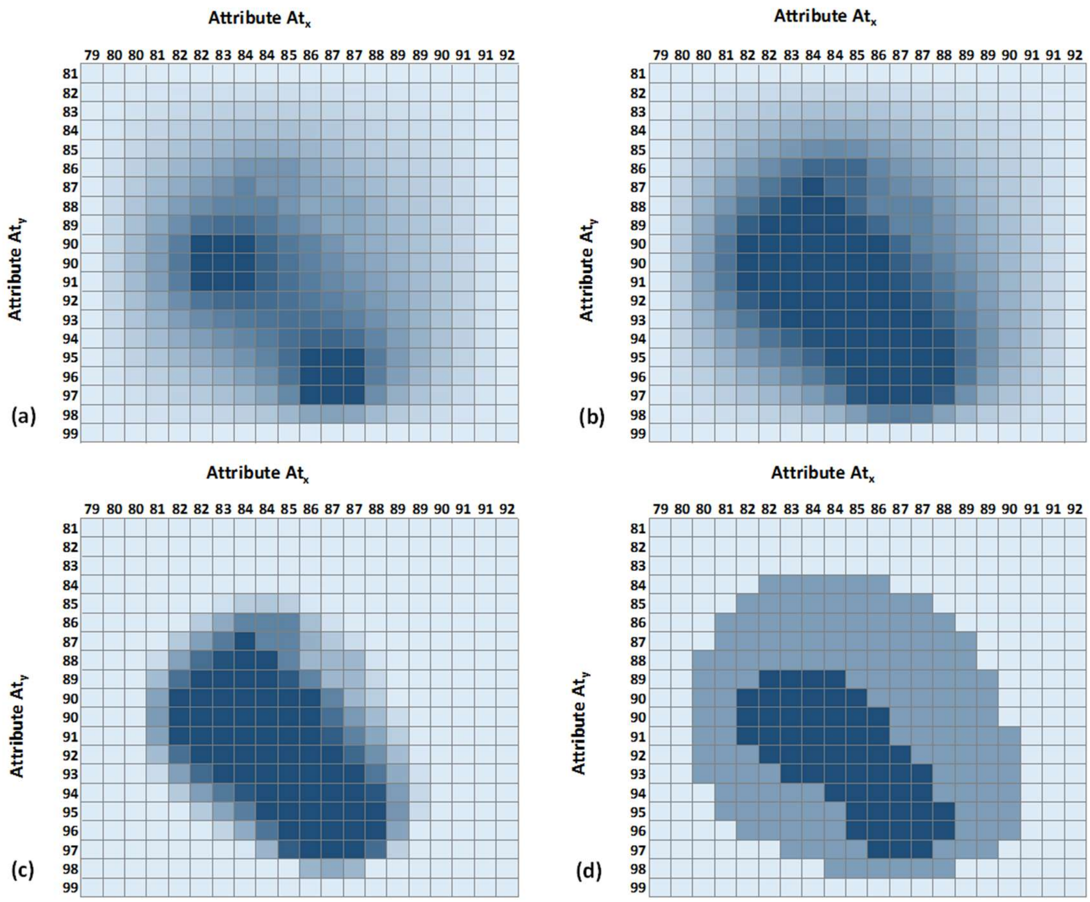

Figure 92 Four Point PFAL Heat Map.

Even with relatively few data set points (4), the PFAL process provides a good indication of relationships between the points and possible zones of similar utility. It also identifies islands of difference and possible boundaries to infeasible zones. Through a process of interpolation from known data points, using a structured relationship model, a richer picture of feasible design point locations emerges from the available data. This enhances the sparse data available to the concept designer and shows it in context with a more complete map of possible designs.

4.3 Norton-Bass Modelling Results

The Bass curve has been used in this study to model demand for engines as they are introduced to the market and complete their production lifecycle. This method was chosen as it fits in with expectations of adoption modelling used for most new product planning activities in industry. Section 3.7 on Norton-Bass models discusses how various modifications to the standard Bass model have developed to account for multi-generational product launches, cannibalisation of existing product in the market and external factors that may affect the take-up rates of new product launches. Although originally developed to model the diffusion of new technologies, the modified Norton-Bass models can be applied with good fidelity to model the lifecycle of a new variant of an existing product family to meet market demand (Valle & Furlan 2011, Chandrasekaran & Tellis 2007).

Using the Rover K series engine as a basis for modelling the complete production lifecycle of a high volume automotive production engine, Figure 93 shows the annual production volumes across its life. These volumes are for all variants of the engine family. Production capacity for the major 5C components was installed at 235,000 units per annum (UPA). The production equipment consisted of dedicated transfer line systems with installed capacity for the initial production variants (*Machinery and Production Engineering* 1990a). Later expansion of the engine family into 1.6 & 1.8 litre variants required further investments in production equipment to deal with the dimensional changes to the engines, as well as design configuration adjustments to the head and block designs caused by the move from a wet cylinder liner to the 'damp' liner design - see section 2.2.4 Rover K series engine. The production line needed changes for the later V6 variant of the engine, as well as a capacity increase for additional volumes in 1996. This later expansion had learnt from being constrained by the first investments in dedicated equipment and used flexible machining centres so that they could be more amenable to future changes in design (Birch 1996, Howard 1996). The actual production volumes for the K series are compared against a modified Norton-Bass model. Left truncation of Bass adoption models replicate the launch and decline profiles of product lifecycles more accurately than standard Bass models, which are more suited to new technologies (Kim & Hong 2015). It can be seen that the modified Norton-Bass model replicates new product variant lifecycles with good fidelity.

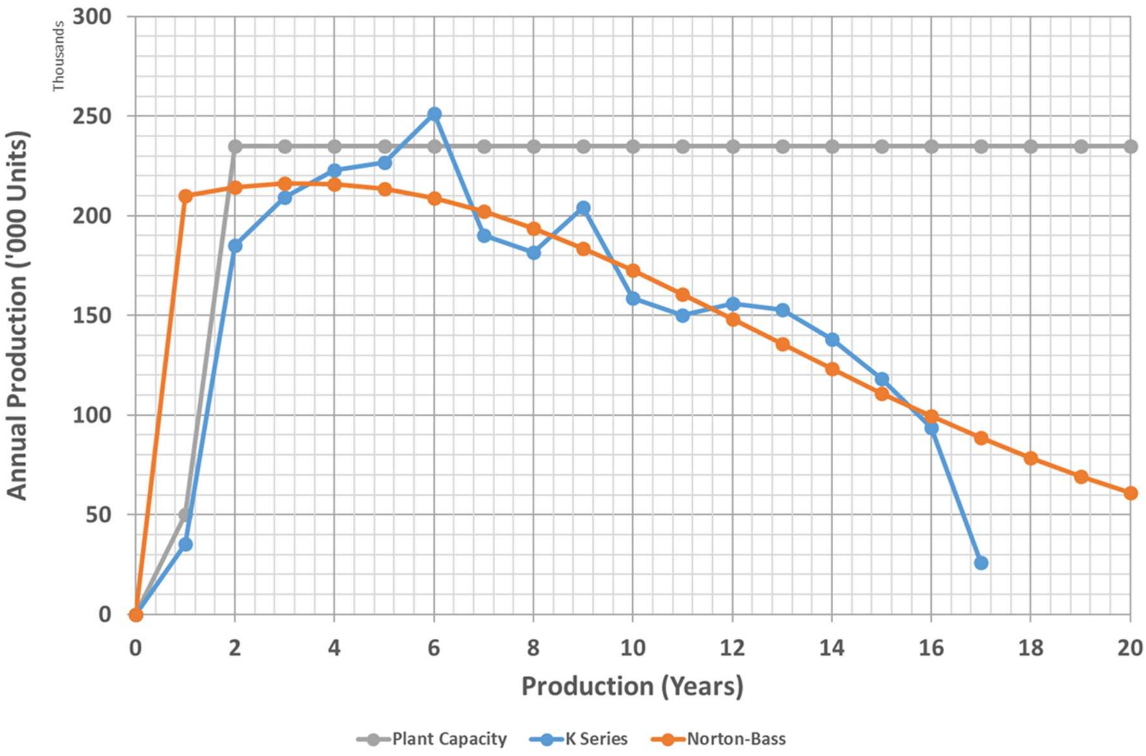

Figure 93 Rover K Series Production with Modified Norton-Bass Model.

For the types of products that require dedicated equipment and involve resource intensive set-up and shut-down, such as engine production lines for higher volume internal combustion engines, a fixed capacity of machining and assembly line will be installed. There may be a ramp-up and ramp-down period, but the idealised annual production volumes will be at a stable state to aid efficient operation and utilise the production facility to its maximum. In reality, there may be some variation in actual production volumes on an annual basis due to shifting market demands, unexpected shutdowns and supply issues or other factors that may mean the plant does not operate at a steady state condition. Queueing theory from operations research would suggest that most manufacturing plants need to have some capacity for short period issues (Mijares 1996). Thus operating capacity is usually set at 70-80% of maximum capacity. The International Motor Vehicle Program (IMVP) study on automotive engine pant efficiencies (Whitney, Peschard & Artzner 1997, Whitney & Peschard 1996) showed engine plants operating at typically 65% efficiency, which confirms other research that shows that many automotive plants operate at capacities as low as 53% (Toilio & Matta 1998). The modified Norton-Bass model provides a reasonable fit of production volumes for engines variants over the lifecycle of the production volumes for sample products.

The cumulative production volume for a given engine production life is shown in Figure 94. This shows a rather shallow form of the typical S curve shape for an engine in production for 16 years. The left truncated sharp start-up of production and the rapid decline and end to production account for the nature of this particular curve not following more of the traditional S shape. The total production volume of 2,700,000 units is based on data for the Rover K Series engine from Hammill (2008).

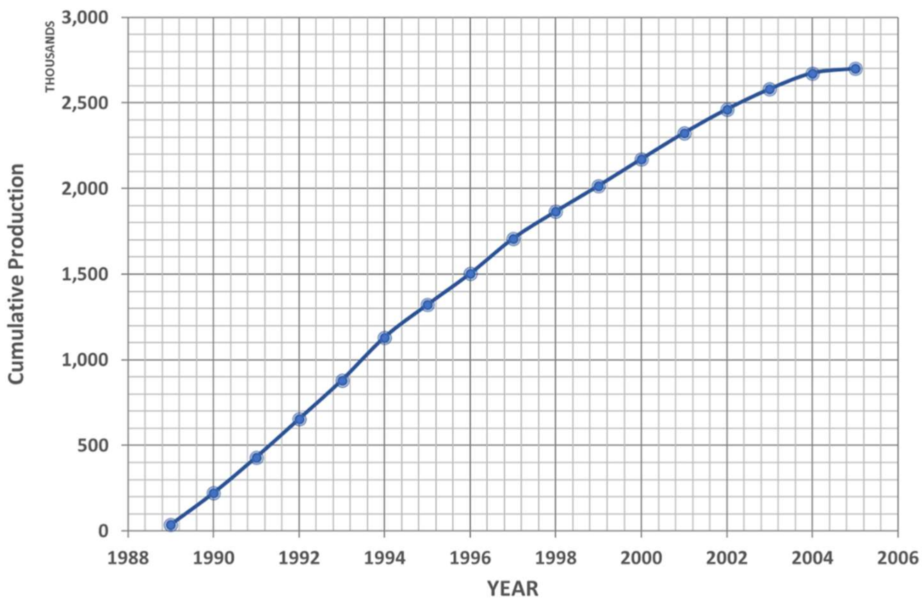

Figure 94 Rover K Series Cumulative Production.

The Norton-Bass models can be applied to initial planned versions of the engine as well as subsequent variants that were launched at later dates. Engine variants are subject to replacement at five years by additions to the product range or replacement products. This is typical of the lifecycle process in engine design, where engines of modified configurations or major updates will occur throughout the overall production life of the product. These changes may be different displacement options, major valvetrain changes (2V to 4V) or other architectural configuration change that requires major capital investment affecting the 5C parts. With the introduction of a newer version, the Norton-Bass curve models a reduced rate of uptake as any change in a product is associated with a shift in adopters to contain a larger proportion of ‘innovators’ as opposed to ‘imitators’. This is borne out by data on serial release of engine variants to the market. As the revised or updated variant is better matched to current market conditions its overall potential market size is greater than that of the original variant had it been left in the market unaltered. However, its overall potential volume is reduced due to there being a finite market life for that type of product. Even the updated variant will have a finite life and sales will ultimately soften and peter out, requiring another update to pre-empt this stage or else allow the product to naturally come to end of life.

The cost of these changes is modelled as returns on investments made. Total development costs for the Rover K series engine were £250M (Ryder 1975). Figures for initial production equipment investments for the Rover K Series engine range, including the gearbox, were £200M (Hammill 2008). These numbers are concurred in articles in the trade press at the time of the manufacturing plant starting operation (*Machinery and Production Engineering* 1990b), with £125M being for the engine and £75M for the gearbox. Data on the cost of change was drawn from internal investment studies on known engine projects (Agile 2005). These studies also provided estimates of the costs of individual components and sub-systems costs for capital investment for a new engine program. Capital investments for the components affected by bore/stroke changes are shown in Table 6 as a percentage of total engine capital investment. The proportion of the original engine manufacturing investments that are affected by the 5C components are 45.8% of the original total investment. This aligns well with figures for the Rover engine investment of £40M for the cylinder head, cylinder block and bedplate. Adding in the crankshaft and connecting rod investments brings this figure to 48% of the engine total investments. The Agile study further indicated that changes to these systems to adapt to a revised configuration, once installed and operational, were typically 35-40% of the original cost shown in Table 6.

Engine System	Proportion of Total Engine Investment
Crankshaft	9.7%
Block	16.8%
Heads	14.4%
Conn Rod	4.9%
Total	45.8%

Table 6 Proportion of Total Engine Manufacturing Investment in 5C Components. Adapted from Agile 2005.

Estimates of the cost of building flexibility into a dedicated production line for machining and assembly are in the order of 15% (Fine & Freund 1990). We can therefore use these figures and apply them to the example of the Rover K Series engine to assess the impact scenarios for change, with and without flexibility built into the production line equipment for the major affected components.

Taking the initial investment for the engine to be the £125M figure referred to in trade publications and press releases from Rover, we can model the returns expected over the life of an engine production life. Six displacement version of the K Series engine were produced over its life from 1989-2005. This is the period of Rover Group ownership of the K Series engine and is when the major production volume (2,700,000 total) was produced. The intellectual property and machine tools for the K Series subsequently passed to first Nanjing Automobile Company Group (NAC) and then Shanghai Automotive Industries Corporation (SAIC). The engine underwent major updates, was re-designated the N Series and has been in production up to the present time. Due to the relatively major changes made and the low volumes produced under NAC & SAIC ownership (<7,500 units made over 5 years), this period is discounted in these calculations. We can therefore assume a per displacement variant of around 450,000 total volume on average. The production life of each displacement version varied between 6 and 16 years, averaging 10.2 years. The engines were produced by a subsidiary company of Rover Group called Powertrain Ltd and 'sold' to the vehicle division for £1200 per unit. Material, labour and overhead costs for the engine were approximately £1,100, leaving a nominal ‘profit’ for Powertrain Ltd of £100 per unit (Rover internal data).

A proxy model was constructed for the Rover K series engine, as actual variant volumes are not available. There is some confusion in the published material over all of the engine applications that are contained in the production volumes. Consideration of all uses for the engine, including non-Rover products such as Caterham, Lotus, Land-Rover and Kia, suggests a total lifetime production volume of 3,600,000 may be more realistic for this type of engine. This includes an increase in Rover usage volume to compensate for the later life tail off in volumes shown in Figure 95 which occurred due to the political situation at the time and a lack of investment during that period.

Putting these figures into a return on investment calculation, discounting interest and time value of money for the purposes of this exercise, we see the characteristic payback curves indicated in Figures 97 & 98. These figures model the investments for the change affected 5C components only (£57.25M). The models show an initial launch of the product design, followed by four variants to the engine architecture over the manufacturing life of the family of engines. Each variant is spaced every 5 years, as representative of typical engines lifecycles based on the analysis of engines in section 2.2.4.

Figure 95 shows the case of dedicated equipment used to minimise initial investment costs. This is the usual strategy adopted by manufacturers for high cost capital investments in engine programs. Subsequent changes in design to 5C components incur a reinvestment cost of ~18% of the original capital equipment investments. This is calculated from an assumption of 40% cost of change (see discussion above) to the 5C parts, which account for ~46% of the original investment. The projected revenue is generated by the modified Norton-Bass model. The first variant has a higher sales projection than subsequent variants and a slower take-up rate - see discussion above. The chart shows how each new variant incurs a cost which must be recovered by additional sales. Each variant launch extends the product life in the market, but itself must be refreshed by new variants, with their own consequential additional investments costs, at intervals. The bold line indicates cumulative revenue generation over the life of the exemplar engine family.

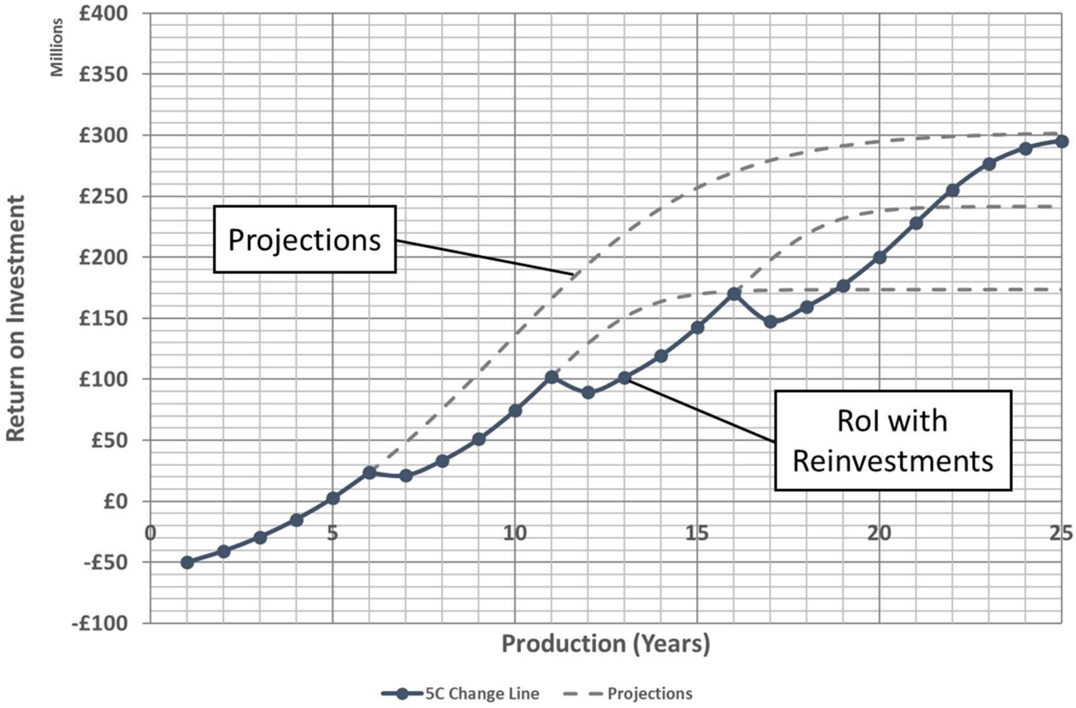

Figure 95 Dedicated Equipment Return on Investment over the Engine Family Production Life.

Figure 96 shows the same analysis conducted for flexible manufacturing equipment. There may still be some investments required for new variants, but these will be typically below 15% (Fine & Freund 1987). If the original equipment has had sufficient expansion capacity built in for architectural changes, as would be the case if a PFAL process were adopted, these reinvestments may be minimal and considerably less than the conservative 15% number typically used for flexible equipment. A figure of ~5% has been used in this model to account for the advantages of adopting PFAL, but whilst recognising that a certain amount of equipment adjustment would be necessary. This takes into consideration that even with modified adaptive landscape methods, there is always a degree of uncertainty in what capacity for change is required. Conservatively, this cost has been applied each time a variant is introduced.

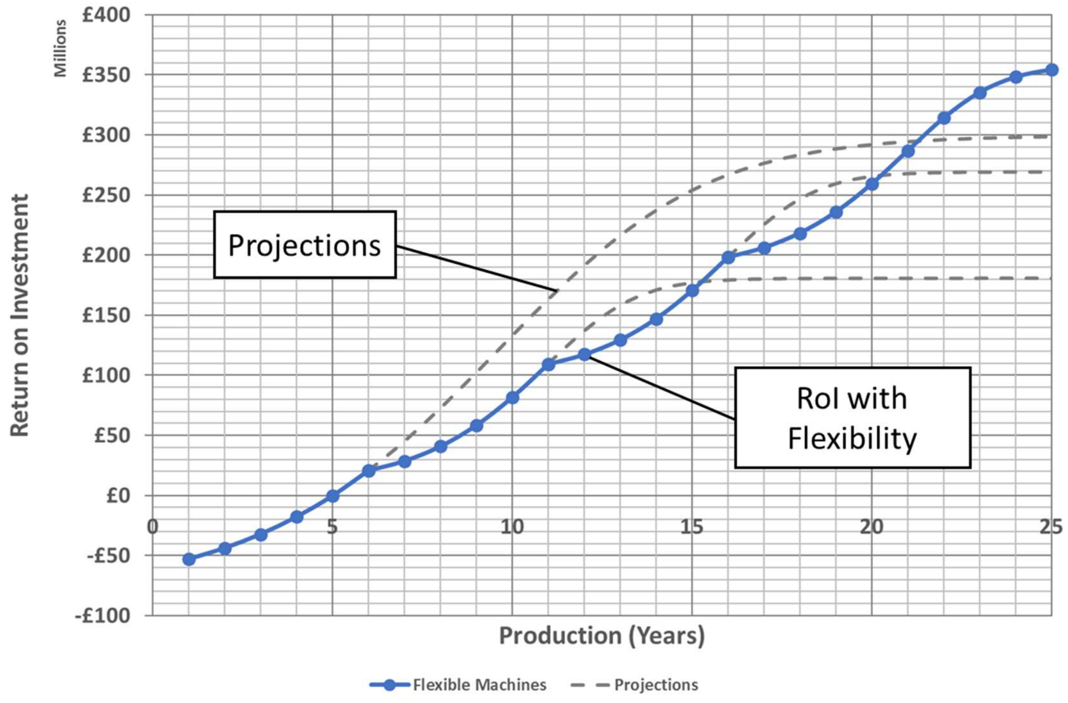

Figure 96 Flexible Equipment Return on Investment over the Engine Family Production Life.

The same constraints of number of variants and cycle change has been applied to both fixed and flexible manufacturing equipment environments. Figure 97 shows a comparison between these approaches. Over the first iteration, the dedicated equipment does indeed show a better return, as it incurs a lower initial investment cost. It is this benefit that is so attractive to senior management when making business case justifications for the engine at the start of its production life. At that point, there are many uncertainties about how the product will be received in the market and the potential reaction of competitors. The first variant introduced at year six provides a slight edge for flexibility over dedicated equipment. This suggests that if there is *any* possibility of a later variant being introduced during the production life of the engine, then the best overall investment policy is to build in excess architecture capacity into the manufacturing equipment, including flexibility for changing head bolt locations, machine platen sizing, transfer system silhouette profiles, etc. The evidence of the Rover manufacturing upgrade investment being made in flexible machining centres and moving away from dedicated equipment supports this (Hammill 2008).

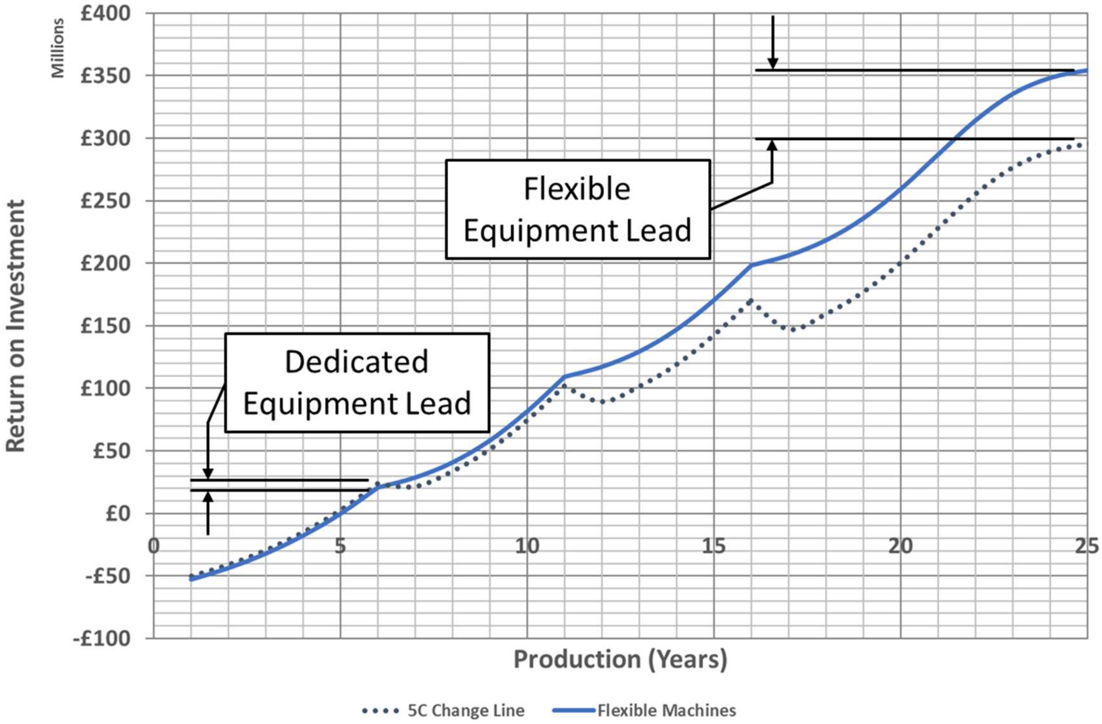

Figure 97 Comparison Between Investment Strategies Return on Investment over the Engine Family Production Life.

The analysis of engine lifecycles conducted in section 2.2.4 shows that unplanned variant introduction over the life of an engine family is the norm. This reinforces the benefits of excess capacity in production equipment for architectural changes. The additional revenue return increases with each subsequent variant launch, as shown in Figure 97. The modified adaptive landscape process, including a PFAL methodology, can enable planning of the scope and degree of dimensional capacity required.

With an average variant production life of 10.2 years, we can model the replacement strategy of absorbing the additional £22.9M costs to change the existing dedicated production equipment for the 5C parts versus the slower payback rates for the flexible equipment that does not require change when a new variant is introduced, provided it is within the limits of variation allowed for by the plateau design capacity built into the original production line specification.

If the variant is not required by market changes or other demands, the risk is that the potential additional costs of flexibility built into the machine tools will not be utilised. This represents a sunk cost that does not get a return on the investment made.

This amount (~5%) becomes trivial when considering not only the higher costs of more extensive changes required to dedicated equipment (~18%), but also the amount of disruption and interruption to production that is required by major machine changes. It may be possible to mitigate any costs of flexibility by building in geometry capacity, say for a larger engine dimension to be accommodated in production line platens and jigging, without additional flexibility in the machine itself. This comes at a cost of slight increases in equipment purchase price and size, with marginal increases in material costs to produce the production equipment.

A review of the development history of powertrain units over their entire production life would suggest that in most cases, a degree of geometric capacity growth in production equipment would benefit the production life cycle costs of the engine. There are additional benefits in adopting this approach as the change time to introduce a new variant is much reduced, requiring no more than minor adjustments to use the new geometry capacity already built into the machine tools. The need for lead-times on modified equipment for the line and any downtime associated with switching production over to the new variant is also eliminated.

4.4 Retrospective Engine Lifecycle Analysis

Engine adaptive landscape analysis seeks to improve initial concept design choices so that they are resilient to unknown drivers for change throughout the complete production lifecycle of the engine. The life of an engine design from concept through to the end of its production life may extend over many years. This presents a challenge when looking to validate the method. The high cost of producing engines, even as prototypes, and the long time-lines for product evolution prohibit experimental testing of the PFAL process. A fundamental factor in the need for resilient solutions is the uncertainty of future needs. A review of historical engines evolutionary paths can provide us with retrospective data on how actual engines designs evolved from their original conception through to end of production life.

The PFAL technique looks at assessing concept design options and their potential impact over the entire production life of the engine. The high cost of producing an engine, even a prototype unit, means that only favoured designs are carried forward for build and testing. Prototype engines may have materials costs in the range £20,000-£80,000. Even on large programs that are well funded, option choices are limited to those few configurations that have a high probability of going forward to production. Increasingly, computer modelling and analysis are used to evaluate options to reduce the need for expensive physical models. This is because the testing and validation phases of the programs are responsible for the highest engineering cost - typically 60%-80% of total program cost due to material costs, consumable costs like fuel, facility charges and long duration testing for durability and reliability.

Architectures considered for the concept of a new engine are generally limited to a single preferred option with its main variants from an early stage of the design process. The cost and resources required for detail computer modelling and physical hardware testing limit the variety of options that can be considered. Several options for testing configuration alternatives of more radical designs may occur if there is a high degree of uncertainty around a new technology or design, but these will be highly constrained. For both budget and time reasons it is unlikely that an engine program would spare the resources to explore smaller changes enabled by a plateau design approach using physical prototypes, such as exploring bore size variation and packaging impacts.

The most challenging aspect of validating a PFAL model with reality is that it takes an open design brief at the start of the concept design and then seeks to assess the impact of configuration changes over the production life, which may be 10-20 years in length. The entire process time from concept to engine end of life may be 25 years or more. Clearly evaluating competing options over this period is impractical. An alternative approach is to retrospectively assess what might have occurred with an historical engine with a known development history.

The limitation of reassessing historical engine development is that we need to be careful of hindsight bias. Each engine design and the need it aims to address are to a large extent unique. This means that designer choices will not always be constrained in the same way. The choices of plateau and flooded plane definition will not therefore, be consistent across designs. Nonetheless, it is useful to see various 'what-if' analyses of configurations and how they might have altered the need for engines to incur additional capital investment over their production life or even avoid premature removal from the marketplace when they proved non-viable due to changed market environments.

The Rover K series engine was selected as an exemplar model for testing the utility of the PFAL process to an engine program. This engine was selected as it is well documented across its entire product life to end of production (Hammill 2008). The evolution of the various configurations of the engine has been described in literature (Gould 2015). The concept design philosophy has been described by the original designers (Hiljemark, Knight & Shillington 1990), as well as its subsequent development (Stone, et al. 1990). Manufacturing costs and the investment in production equipment, was available from trade publications and through personal contacts established with design and manufacturing engineers at the former Rover Company.

4.5 Engine Designers' Perspectives

Engines concept designers were interviewed to obtain a better understanding of the drivers for new engines programs, the processes used in determining initial configurations of powertrain design architectures and the evolution of engines over their production life - see section 3.3 Engine Designer Interviews. In particular, a picture emerged of the changes made to the major geometry of engine designs over their production life and how these deviated from expected developments of the engine that were laid down with the initial concept.

The product development professionals all had experience of the design and development of engine concepts. Figure 98 shows the primary role that the interviewees play in the concept design process. Several interviewees had performed multiple roles during their careers, such as a concept designer moving into a project leadership role. This gave them a broader perspective on the complex and conflicting requirements of developing a concept to achieve a range of financial, functional and logistical targets. All participants worked in highly collaborative environments where decision making was done through negotiation and compromise.

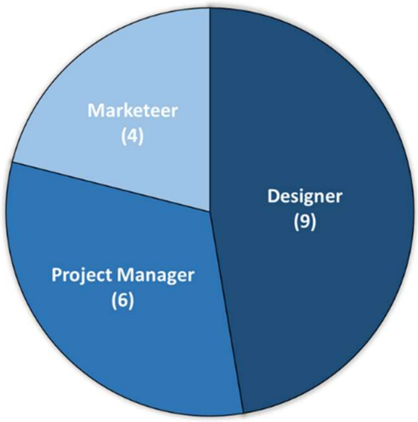

Figure 98 Interviewee Role in NPD.

Figure 99 shows the relevant experience level of the interviewees. The average number of years' experience in the design and development of engines was 16.1 years. The engine concept designers had a broader range than the other role categories but also included some of the most experienced product developers with up to 30 years' experience.

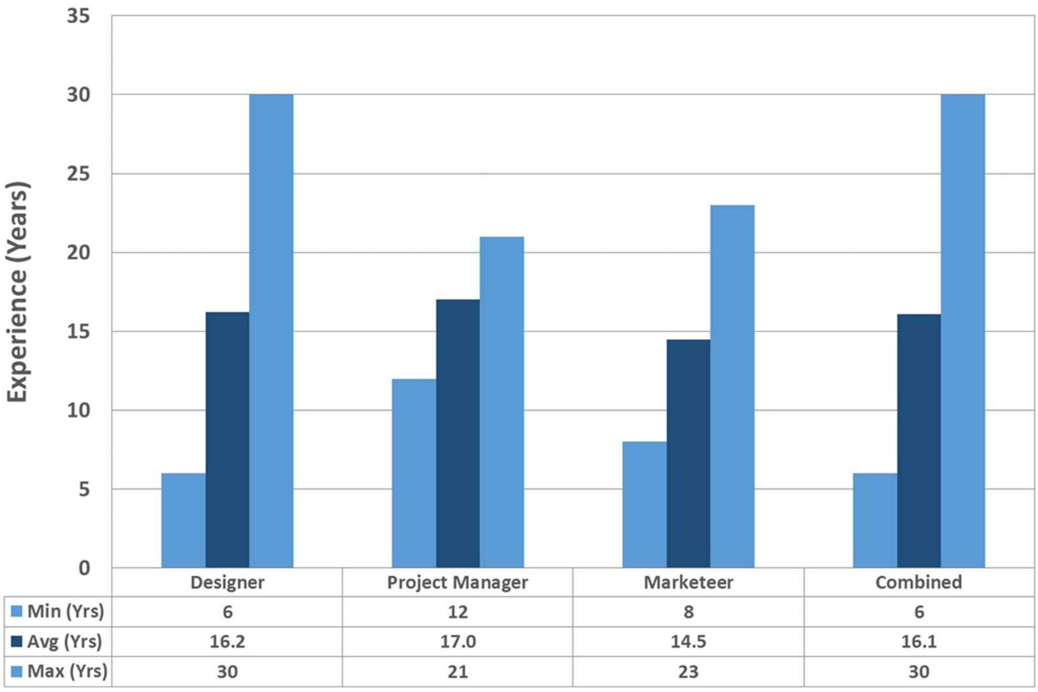

Figure 99 Interviewee Experience Level.

The respondents were asked about the expected planned life cycle of the new engine programs on which they had worked. These were the expectations of the production life of the engine after initial launch, before replacement or any major upgrade to a particular configuration. It may be that several variants of the engine were planned from conception with staggered introduction dates but the lifecycle considered here was for the family of engines as a whole, not for a single variant.

The average expected production life of a new engine program was 10.6 years at the concept stage (Std. Dev.=2.16, Max.=15yrs, Min.=6yrs). It was observed that a somewhat arbitrary production life of "...about 10 years…" was often applied during program planning. Some review of historical trends for production life within a particular company might be conducted by product planners, but the emphasis was on the date of first launch to market rather than end of life planning.

Figure 100 shows the range of deviations of production life of engines from their original plan. The average deviation was -46%, meaning that the engine had a reduced lifecycle before requiring an unplanned change to major engine geometry. Planned upgrades or variants of engines where the geometry change was incorporated in the concept architecture are not included in this figure. The greatest cause of changes to geometry were either a bore or stroke change to produce a new displacement variant of the engine. This was usually a requirement for a larger displacement to achieve higher product performance targets, but on one occasion was a reduction in displacement to meet a taxation bracket for smaller displacement engines. Reductions in the planned production life of the engine represent a loss of the recovery of any investments made in plant and equipment not fully written off over the actual production life. Given the dedicated, bespoke nature of 5C manufacturing equipment used in high volume engine production, residual values of assets are relatively low compared with flexible machining centres that can be re-purposed to produce other component designs. In order to achieve the objectives of the original investment business case, it is therefore important to extend the useful productive life of major capital equipment investments to the greatest extent.

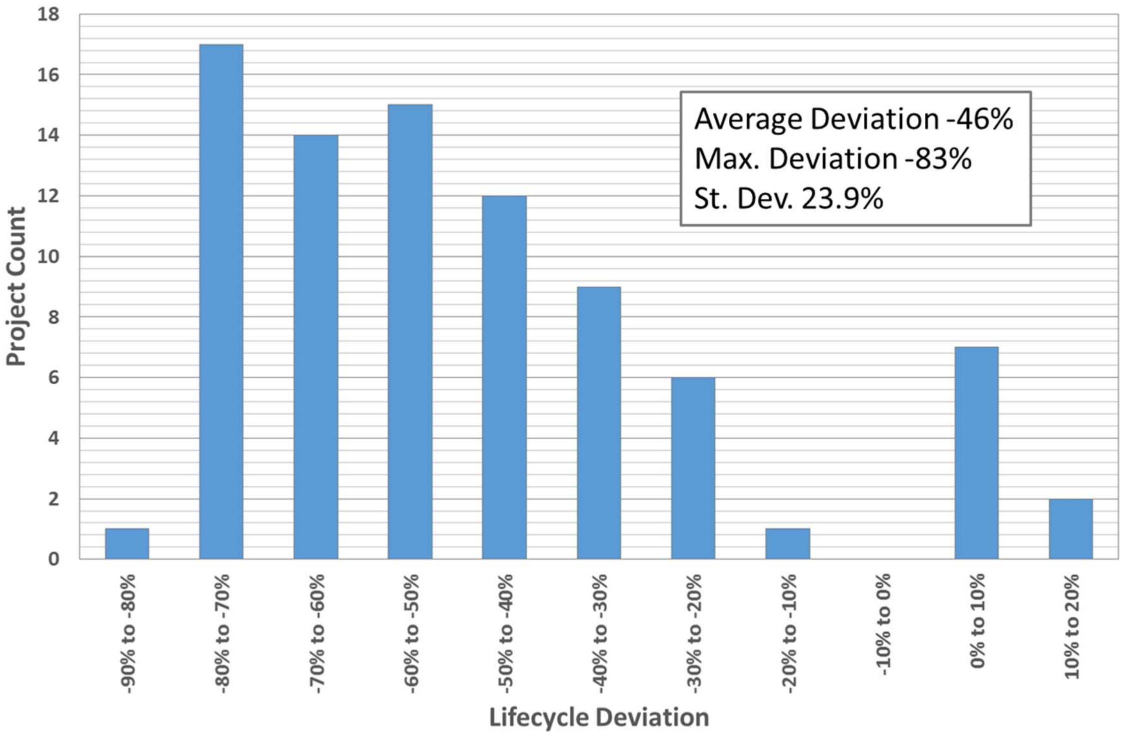

Figure 100 Engine Production Life Deviation from Plan.

Figure 101 shows the deviation of the capital investments in the experience of the product developers interviewed. This shows that over the production life of the engine family an additional 17% of the original capital was required to cope with product updates and changes. This is lower than expected given the given the frequency and extent of changes observed across the projects considered. Each new project, including upgrades and variants of existing engines, tended to be considered as an independent business case and was rarely compared to the original product launch business case. Indeed, there appears to be a remarkable dearth of reflection or analysis of engine family whole life business case tracking. The estimates for extension costs of unplanned derivatives of existing engines should therefore be viewed with caution as it appears to be under estimated when set into the context of the frequency and extent of unplanned 5C geometry changes required on most projects over their production life.

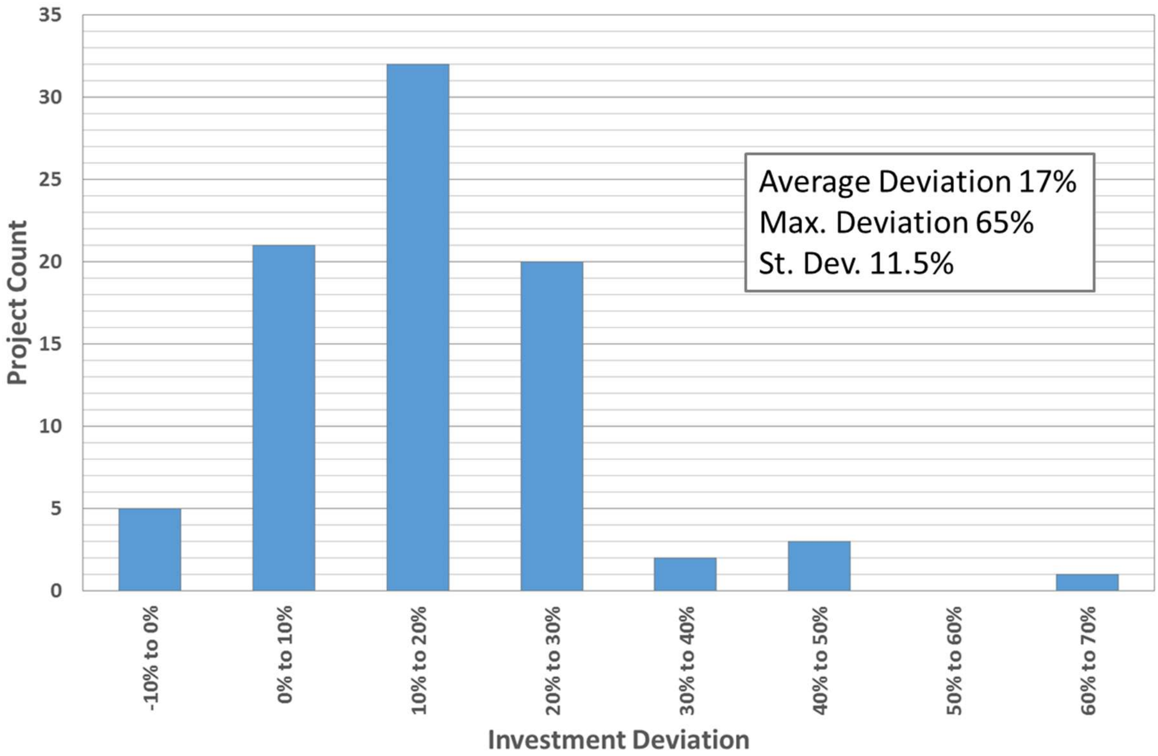

Figure 101 Deviations to Plan of Engine Manufacturing Equipment Investments.

The actual production life of the projects reviewed was 5.5 years before a major unplanned geometry change was required (Std. Dev.=2.04, Max.=12yrs, Min.=2yrs). This means that the average engine production life was 46% shorter than planned, with some programs requiring significant changes and upgrades within two years of entering production. The figure of 5.5 years for average production life is shorter than the data obtained for automotive engines in the European market of 8.8 years (Std. Dev.=5.69, Max.=34yrs, Min.=1yr) for petrol engines (Figure 22) and 8.5 years (Std. Dev.=5.28, Max.=29yrs, Min.=2yrs) for diesel engines (Figure 21). A production life of 5.5 years before significant geometry change is more in line with data on motorcycle engines (Autodata 2013) which shows an engine production life of 5.4 years on average (SD=2.88, Max.=18, Min.=1) - see Figure 23. The differences may reflect the types of projects undertaken by consulting companies which tend to be higher performance derivatives, with shorter market life.

The experiences of designers during the concept phase of projects was explored during the interviews. A review of project plans for typical engines programs shows that <5% of the project duration is allocated to the concept phase. This is confirmed by examples of project plans published by Hoag and others (Hoag 2006, Scheid, Houben & Schwaderlapp 2003). During this period, the concept designer, sometimes referred to as the engine architect, is often working in isolation or with a small team of cross-functional stakeholders, to define the basic engine configuration.

Major decisions on the layout of the engine such as bore, stroke, displacement, number of cylinders, maximum performance levels, etc., are determined at the concept stage. Once set, the program moves forward with more detailed performance modelling and computer aided analysis (Computer aided engineering - CAE). Further refinements of the concept configuration follow an evolutionary process of adjustment and the base engine architecture is only revisited if an insurmountable conflict in requirements arises. The parametric nature of engine design means that even small changes can be challenging to accommodate due to the snowball effect of cascading impositions on neighbouring geometry - see section 2.2.6 Concept Design Process. There is therefore an understandable reluctance on the part of designers to change architecture once the concept geometry has been set.

This tendency to fix architectures early and iterate to an acceptable solution set, rather than fundamentally review configurations if they are found to be unsatisfactory, has been observed many times. Most notably, the MIT study into automotive firm's operations conducted under the International Motor Vehicle Program (IMVP) from the mid-1980s, investigated product development processes and manufacturing operations within the automotive sectors in the USA, Japan and Europe (Womack, Jones & Roos 2007). This seminal study is credited with being one of the first instances of a wider dissemination of the philosophy of lean production and the Toyota Production Process (TPS).

One of the findings of the MIT study was that traditional automotive manufacturers would converge on solutions rapidly and then spend considerable amounts of resource and time in making them work. This was particularly true of USA and European companies but also applied to some Japanese manufacturers. Toyota had developed a so-called *set-based* design approach which developed several possible solution sets in parallel and deferred decisions until the last possible moment (Ward, et al. 1995). This approach was seen as costlier in the initial stages, but had the potential to reduce delivery time over the whole engineering program and reduced risk, as there were developed alternatives to a single path solution always available. Although the benefits of set-based design structures in engineering programs have been well developed, they are still rarely applied (Sobek, Ward & Liker 1999). This is principally due to the perception that development of several solutions in parallel is costly and resource intensive (a known cost), versus the potential of needing an alternate solution set if issues arise with the preferred embodiment (an uncertain cost). This reflects the challenge with short-term cost savings leading to longer term additional costs, which is at the heart of the issue with building resilience into the manufacturing capital investments.

Concept designers are under pressure to converge on a solution set early in the process so that the rest of the new product development team can get started on modelling, prototype testing and development activities, which consume the majority of the new product development process resources and time (Scheid, Houben & Schwaderlapp 2003, Smith & Reinertsen, 1997, 1992).

The skill set of a concept designer lies in their ability to conceive new configurations of product, working with limited information. The product architect takes a holistic view of the product configuration, unlike their developmental engineering counterparts who tend to be very focused on solving a specific issue or undertaking a particular product test. The role of concept designer usually falls to the most experienced engineers within the group; those with a broad exposure to the implications of trade-offs between competing requirements for the product. The path of concept development is one of satisficing, rather than optimisation.

Compared to more traditional engineering roles, the concept designers task can be characterised as more open ended, uncertain and intuitive. Even in an age dominated by computers and sophisticated mathematical simulations, concept design remains an essentially lone, cerebral activity. The designers interviewed described their work process as much less analytical than later stages of the engine design process. Mathematical analysis relies on the availability of data to perform analysis and this is usually in short supply at the beginning of the design process.

To help with the consideration of concept options designers seek tools, techniques and processes that have certain particular characteristics:

Simple - Concept designers tend to be less analytically focused than their developmental counterparts. Combined with a dearth of data, designers seek relatively simple and easy to apply processes and tools. They do not feel that they have the luxury of time or the skills to apply to complex mathematical models or complex evaluation procedures. This is a reflection of the resource limitations, time pressures on the concept designer, as well as the inherent bias of creative thinkers.

Quick - The processes adopted by concept designers need to be fast, adaptable and amenable to quick iteration. This stage of the new product development process is highly dynamic, with rapid changes of direction the norm. The tools and techniques brought to bear need to be intuitive to use and easily adopted.

Visual - Communication with other stakeholders is an essential aspect of all stages of the new product development process, none more so than the establishment of the basic first configurations. In line with product architects tending to be less analytical in approach, they have a bias to visual thinking styles. Dealing with complex evaluations of multiple criteria for decision-making can be greatly enhanced by being able to visualise the interactions and trade-offs under consideration, especially for non-engineering stakeholders.

Developing a decision-making process that embodies these attributes ensures that the methodology directly addresses the needs of the concept designer and the early stage product development team and is therefore more likely to be adopted.

An example of the PFAL process was presented to a sub-set of six of the original participants in the NPD stakeholder interview group. An explanation of how the process works and the possible benefits were described and the product developers were asked for feedback on the process. The product developers recognised the issue of needing often to evolve engine designs in ways not considered in the original concept, necessitating major changes to engine architecture. They were positive about the potential benefits of adaptive landscape thinking in concept design giving a rating of 4.3/5.0 on a Likert scale when asked “Do you think the PFAL process would help early concept design decision making”, where 5 was ‘Very beneficial’. They were less confident about applying the technique giving a rating of 3.8/5.0 to the question “How easy do you think the PFAL process would be to apply”, where 5 was ‘Very easy to apply’. This may be due to their lack of familiarity with the technique as when asked “Would you apply the PFAL process if benchmarking adaptive landscapes were available, with 5 being ‘Very likely to apply’, a rating of 4.8/5.0 was obtained.

The PFAL process was considered by the product developers to have utility and to be a useful addition to managing the concept design decision making process by taking a broader view of the whole production lifecycle of an engine family.

4.6 Concluding Remarks on the Study Findings

This chapter made use of the adaptive landscape model to assess the potential impact on the concept design definition of a new engine. Using the Rover K Series as an example, the model was applied using the data on production volumes, lifecycles of variants and costs of change. The model indicates that the benefits of resilience capacity being considered in engine architecture decisions on key geometry choices can be modelled and demonstrated to stakeholder groups. The Norton-Bass adoption model shows that the short-term costs of additional flexibility in manufacturing equipment and tooling configurations is invariably worth the additional investments costs due to the high probability of uncertainty around future engine geometry changes.

The next chapter summarises the benefits and limitations of applying the PFAL satisficing model to a product design. It discusses future developments of the process including automation of calculation tasks and means of modelling dynamic environments.

5.0 Conclusions and Recommendations

The previous chapter presented the findings of applying the PFAL design process to an exemplar engine. This was validated through assessment of investment strategies and simplified return on investment calculations. This chapter outlines the contribution to knowledge made during this study and the benefits and limitations of the modified adaptive landscape method being used, in determining concept geometry choices for manufactured products.

5.1 Introduction to Conclusions and Recommendations

The previous chapter presented the findings of the PFAL process being applied to an exemplar engine, with validation through investment modelling and gaining commentary from practising engines development engineers. This chapter presents the contribution to knowledge that the application of modified adaptive landscapes can make to concept design geometry planning. It discusses the use of PFAL design in future engine concept configurations.

The benefits and limitations of the PFAL design process are discussed. As an analogous process, it has limitations of being able to be completely translated into another discipline area. The adaptive landscape is a guide to understanding viable configurations in the design space and does not profess to be an exact analysis tool. It is an aid to decision making. The benefits of the process have however, been demonstrated and the potential of the method has been verified with engines engineers.

A recommendation is made that the process be further developed, to automate some of the tasks that are currently manually performed and to develop the process as a self-contained application with a simple user interface. Given the infrequent nature of its potential use, but the wide range of potential applications in other fields, a generalised tool to evaluate options trade-offs using limited data is worthy of further development. Possible alternative forms of surface and methods of interrogating these surfaces to obtain better quantifiable information are discussed in Appendix C, together with a more detailed description of the PFAL process.

5.2 Contribution to Knowledge

Existing processes for concept generation in IC engines are ill-defined. As an activity that occurs infrequently and with limited design input information, interviews with product designers has shown the process to be somewhat shrouded in mystery. The use of formalised new product development processes is now well established (Ulrich & Eppinger 2015, Gronlund, Sjodin & Frishammar 2010). Each stage of the design process can be defined, with the required activities outlined and tracked. The 'fuzzy front end' of design is more difficult to define. It is a relatively brief stage of the design development process that by the nature of being unconstrained and open is rather chaotic (Kalluri & Kodali 2014). Indeed, the purpose of the initial design concept layout can be thought of as bringing order to the needs of the market. The first concept solidifies a design embodiment on which further development can occur (Pahl & Beitz 1996, French 1985). It is not until the concept geometry has been laid out that further analysis of the design can occur, and the configuration can evolve into a final form.

A review of engine concept designs and interviews with product development teams have shown that once an engine concept is defined, it gets fixed quite quickly and is difficult to change. Even in the early stages of development, when no hardware has yet been produced, the resources and effort required to significantly modify a design architecture can be daunting for the product development team. Due to the parametric nature of engine designs, where a change in one dimension may have cascading effects through the geometry of the rest of the engine, it is not a simple matter to make changes to key geometry such as bore and stroke, cylinder block deck height, bore centres, valvetrain geometry or other constraining dimensions. The more optimised the geometry for weight, size or functional performance, the less scope there is for changes that do not have major impacts.

The lifetime of an engine in production is typically 10-12 years, with several variants required to keep the design relevant to the marketplace and conform to regulatory requirements over that time. This means that required changes to geometry may be unknown or at least uncertain at the point when the concept geometry is established. Capacity must therefore be built into production equipment for geometry change, that is uncertain, but likely. Excess capacity comes at a cost and must be justified. The challenge for the designer is to have a structured, rationale for making decisions on the geometric growth potential of key engine parameters under conditions of uncertainty.

Following the analogy of evolutionary development, the biological world provides a model for uncertain but necessary morphological change for survival in dynamic environments. The body plan of plants and animals have survived because they are a suitable 'fit' to their environmental conditions. Fitness landscapes are used in biology and ecology to show the fitness trade-offs of different attributes of animal morphology, function and behaviour. In particular, they provide a mechanism to assess the resilience of morphological forms to changes in the environment, often working with sparse data.

Adaptive landscapes proposed by Sewall Wright in 1932 as a means of understanding biological fitness, can be used to model other forms of evolutionary development. Building on the use of genetic and adaptive search techniques in engineering design (Parmee 1996), the adaptive landscape theory has been applied to product design evolution. A modified adaptive landscape process has been developed to allow designers to not only consider the extant designs that are known to be viable, but also to extend the search space by moderating the landscape form to account for potential new developments or constraints.

The PFAL design process provides a structured, staged process for development of a robust concept geometry that will be resilient to foreseeable change. It is grounded in known heuristics drawn from historical developments of products relevant to the application under consideration, but also allows for speculative inclusion of deviations to current trends based on the expertise of the concept designer and the inputs of the wider product development community of stakeholders.

The PFAL process takes what has previously been a closed cognitive process, occurring in the head of a lone designer and translates that to a visual representation that can be shared with the wider stakeholder group. This includes non-technical experts who might otherwise struggle to follow the arguments of functional technical trade-offs in geometry selection. Making design trade-offs explicit at an early stage in concept development allows for a richer conversation about fitness values and achieving a balanced design to meet multiple complex needs.

The use of modified adaptive landscapes enables future key geometry changes to be enabled with less cost and disruption to capital intensive existing production equipment. This extends the useful life of product families in production. The extension of product life has both financial and sustainability benefits.

The return on investments made is greater by both being able to utilise existing investments for longer, with longer product lives and by reducing the costs of any necessary changes by minimising the degree of change to equipment that may be required. Products that require too much change to existing equipment may not be able to justify the business case for the change. This will result in premature end of life for that product and its associated manufacturing equipment. By building in capacity to absorb geometric change with minimal additional cost, the life of the engine family and the production equipment used in its manufacture, is extended. This provides a greater return on all investments made in the product, including those to design, develop and market the product in the first instance. Lifetime return on investments is therefore maximised.

Beyond financial considerations, the sustainability of the energy and materials used in the manufacture of the product is a consideration of growing importance. Traditional lifecycle analysis considerations have focused on the operational life of products. Increasingly more complete assessments of the social, environmental and financial aspects of product manufacture is being considered. Recent shifts in automotive powertrain designs from traditional IC engines to hybrid variants and alternative competing technologies such as battery electric and fuel cell vehicles, have emphasised the need to consider total lifecycle costs. Many of the newer technologies being considered as alternatives to the IC engine have reduced emissions and energy consumption during the use phase of their lifecycle, but have had greater impacts during the production and disposal phases. Gaining a more complete picture of these impacts to make better informed decisions on trade-offs is essential to ensure that sustainability requirements are met. By applying the PFAL process to concept generation a more complete lifecycle view is obtained of enabling geometric growth potential with minimal change cost over the entire manufactured life of the product. Combined with product life extension, this has great potential for positive sustainability impacts.

Modified adaptive landscapes (MAL) and the PFAL process in particular, offer a new way of thinking about sustainable product lifecycle planning at the concept design stage, including the ability to visualise fitness landscapes of design attributes. The process takes models from the natural world and applies them to manufactured products to configure robust, resilient product architectures. This results in better use of resources and an ability to deal with uncertain future needs.

5.2.1 The Application of the PFAL Process to Future Engine Programs

The PFAL process lends itself well to early stage concept design. The major benefit of the approach is in taking sparse data sets, when little information may be available other than benchmark data points and using this to explore feasible design configurations. It allows the concept designer to consider the implications of product growth and change over time, before any detail analysis has been done and the concept architecture has been set. Detail analysis using advanced modelling methods will refine designs to a point where they can be taken forward as functional prototypes for development and testing.

The process takes heuristic inputs from benchmarking and combines those with the requirements for the engine under consideration in a multi-variate analysis. Considering key pairs of attributes on adaptive landscapes allows the designer to make appropriate trade-off decisions through modelling of the PFAL conditions. This will help lead to not only an acceptable first version of the product but one that provides a more complete view of the full lifecycle development capability of the architecture.

Figure 102 shows the PFAL design process. Heuristic benchmarks and known product performance requirements are used as inputs to the design process. The heuristics from expert knowledge and extant engine benchmark data are set into the context of the specific project requirements and known future developments of technologies, materials and other factors that might materially moderate prior information. A multi-variate analysis will identify those key attributes of the engine family and major geometric parameters that will influence design trade-offs.

A limitation of the process is that it can only consider two attributes on one landscape map. A number of landscapes will need to be considered as a set to get a more complete picture of the design trade-offs, but these should be limited in number to the most significant factors in order to make the process manageable. Adaptive landscapes are generated from heuristic data for the key attributes of the design. These initial landscapes are modified based on projections of possible future developments of the engine family over its production life. This probabilistic modelling is done using information on prior histories of similar engines applications, in order to account for current unplanned variants. This stage broadens out the variant options catered for in the design by incorporating knowledge of prior evolution of similar engines over their production life. The resultant adaptive landscape can then be assessed for resilience to key geometry change. In this manner, conscious decisions on limitations to changes in engine principal geometry can be made. The defined architecture is then evaluated against the multi-variate objectives for the engine family, including cost, capital expenditure, market requirements, regulatory compliance and any other objectives that the final solution must satisfy.

If the current architecture satisfies project objectives with acceptable adaptability limits imposed, then the concept design is ready for release to the product development team for detail analysis and refinement through the product development process. If the architecture does not meet acceptance targets, the process reiterates until a solution is found.

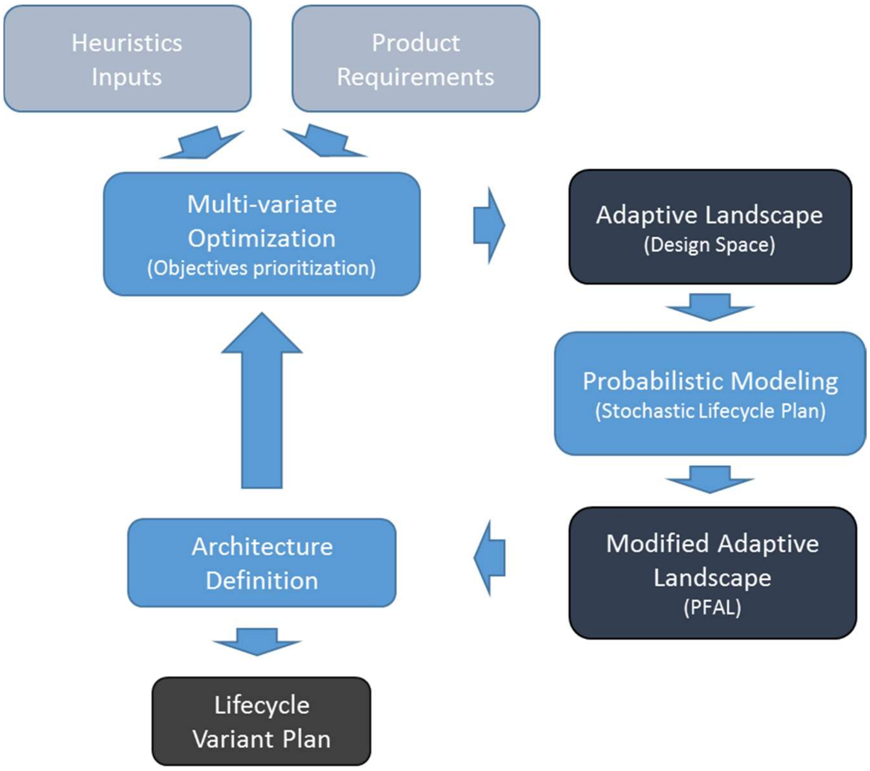

Figure 102 PFAL Design Process.

The concept stage of engine design concerns the free thought consideration of options, as discussed in section 2.2.6 Concept Design Processes in Engine Design. Once viable options are chosen they can be optimised through detail analysis. Testing and validation of engine configurations is a proving process of refinement and verification. Options for major architecture change are limited beyond the end of the concept stage and come with a high cost in terms of the materials and work written off by the change, as well as causing delays to the program. It is therefore essential that exploration of any potential changes is done at the earliest opportunity. Unfortunately, the early stages of the concept design coincide with a period of uncertainty and limited information. It is in providing some level of clarity around the feasible design spaces that could be investigated, the position of extant and competing products to the proposed designs and the relationship between key parameters through attribute mapping, that the PFAL process offers value. The adaptive landscape modelling process is a decision aid to the designer, at a very specific stage of the design process.

Discussions with engine concept designers through the study indicated interest in the approach and a willingness to further explore incorporation of the modelling method in their work. The most commonly raised concern was over the difficulty of persuading stakeholders to accept what some considered a ‘sub-optimal’ initial design, on the basis that it ‘may’ be required to accommodate future, uncertain, changes. Building additional capacity for product architecture change into production equipment, as determined by the PFAL process may incur a cost today (+5% to +15%), against the possibility of a higher, but uncertain cost in the future (+30% to +40%). Studies in risk perceptions show that humans tend to discount future risk and over emphasise current risk (Fenton & Neil 2013, Gigerenzer & Shelten 2002). In making decisions we tend to exaggerate the importance of known risks and weigh them more highly than future uncertainty. In a sense, we tend to live in hope that future risks will not occur. This cognitive bias was evident through discussions in the concept designer interviews. All interviewees were able to describe many instances where unplanned product change once an engine was in production had been both expensive and disruptive to an organisation. However, when discussing future engine programs, the same designers were always positive that “Next time it will be different”.

This represents a challenge in getting acceptance for additional on-cost to a production line investment to be accepted. Perhaps the most productive approach to this issue might be to model the immediate predecessor engine to the proposed replacement engine under concept review. The data on the details of the engine design rationale and its change history should be readily obtainable from internal records, even if this activity occurred sometime in the past (presumably within the last 10-15 years). The costs associated with change on the predecessor engine will be known and relatively fresh ‘lived experience’ for the organisation. This will make the evaluation less abstract and more pertinent to the new engine design review. By modelling a ‘what-if’ analysis of a range of design feature plateau geometries that *could* have been applied to the previous design, it will be possible to quantify the impact of different approaches as cost/benefit analyses. This will quantify the potential for the PFAL approach to avoid costs on future engine configuration choices. In many cases the cost difference to ensure that dedicated production equipment can accommodate flexibility (within bounds) and reasonably foreseeable geometry growth based on priors, is negligible (Lorincz 2008, Koren 2006, Jung & Colgen 1995, Laengle, Griffin & Griffin 1995). Ensuring that a machine footprint can accept moderate change in major geometry incurs no additional cost if done from the outset of machine tool planning. Building flexibility into machines to cover a defined range of geometry changes, such as a range of bores in a cylinder block, can usually be contained within 5%-15% of original equipment capital costs (Pant & Ruff 1997, Fine & Freund 1990).

It is important that consideration is given to the fact that the previous engine operated in constraint and market environments that will be different from future conditions. Technologies will evolve, new competitors will emerge and analysis, engineering and manufacturing processes will evolve, so the adaptive landscape that applied to the previous engine family range is unlikely to translate perfectly to the next engine family. As engine families, typically are in production for 8-12 years (Autodata 2013, Ludvigsen 2001, Smith 1986), the intervening period between when the last engine was conceived and the current time will inevitably mean that fitness peaks need to be updated. However, it is the PFAL process which is being validated through historical analysis, not the specific values that might be shown to have been of benefit post hoc. Once confidence in the approach is achieved with the current stakeholders it can then be brought to bear on the current concept design. The PFAL process is a 'way of thinking' and is aimed at raising consideration of future engine geometric evolution over its production life, rather than professing to derive answers that are correct in any absolute sense.

5.3 Adaptive Landscape in Context

Adaptive landscapes provide a new way to view the design space for product configurations in the context of fitness values for attributes. They allow design attribute trade-offs to be made in a structured manner, giving consideration to future potential for changes to the design geometry.

5.3.1 Benefits of the MAL Process

The modified adaptive landscape process provides a means of visualising design space using sparse data. This enables designers to better understand the limitations of design trade-offs and select areas of the design space that might prove fruitful in producing new designs. The main benefit of applying modified adaptive surfaces is that they engender a design approach that emphasises resilience to change. Consideration is given to potential changes in key dimensional constraints in the design over the products lifetime. Using historical data and an analysis of potential future drivers for change, design geometry is chosen that has growth potential, within constraints, for foreseeable deviations from the initial architecture.

The PFAL surfaces are an aid to communicating the design options and the limits to growth for any particular design. They provide a mechanism to explain complex product geometric and functional interactions to non-expert stakeholders in the design configuration.

Understanding - The PFAL methodology allows the concept designer to envisage the relationships between key attributes in the engine design. By showing the parameters as a profile with a fitness component the decision-making process is enhanced beyond what would be possible with pure numerical analysis. The PFAL landscapes become a visual bridge between the geometric layout of the design images and the numerical calculations of analysis. The landscapes also provide a convenient means of communication with other stakeholders, so that those that do not have an in-depth understanding of the engine design process, or may not have been closely involved in the background calculations, can quickly understand the implications of trade-offs in the design and any limitations that there may be to changes.

Visualisation - The PFAL landscapes are primarily a visual aid, rather than an exact calculation. Their strength lies in the relative position of features on the landscape and their magnitude toward one another. The PFAL has been created using limited data at an early stage and it is important that too much weight is not assigned to any quantitative output in terms of the fitness values. These are early stage estimates and should be treated as such. However, there is tremendous value on have some guidance to the design process to enable more detailed analysis of a limited range of options selected from the PFAL surfaces. Being able to visualise the attribute trade-offs of different configurations provides a clearer understand of complex interactions of multi-variate problems. Although still constrained to three dimensions, by using a series of related PFAL diagrams and focusing on the key parameters the concept designer can present a full picture of the key parameters to be considered in setting the engine concept configuration.

Communication - The process of designing an engine is a collaborative effort with many stakeholders including engineering, marketing, manufacturing, service, regulatory and many other bodies. Even within the engineering group, there will be many sub-disciplines that will have a vital input and who need to be consulted. The process has to start somewhere and usually, working from a marketing brief, a lone concept designer lays out the first concept scantlings. These form the basis of all subsequent discussion. Indeed, until the first rough layout of the engine configuration is obtained, it is difficult to get specific inputs from other stakeholders. It is a truism that many stakeholders don't know what they want until they see it! The PFAL landscapes provide a way for early thoughts on the concept options to be communicated in an easily understood format.

5.3.2 Limitations of the MAL Process

The modified adaptive surfaces are a representation of a fitness field created by comparing two selected attributes and examining the surface generated by the interaction of their parameters. This allows us to clearly see the relationship between the attributes. In order to establish this relationship, we necessarily hold all other variables constant, limiting our ability to see the dynamics of the interaction when subject to a variation in a third variable. A concept design problem will have multiple criteria that will interact in complex ways. Whilst the adaptive landscape aids our understanding of design trade-offs, it is an incomplete picture of the whole design space and must be used iteratively, in conjunction with other optimisation calculations.

A distinct advantage of the PFAL process is its ability to create nuanced surface representations from sparse data. However, this may lead us into a false sense of fully understanding the complete shape of the surface outside the immediate vicinity of the heuristic points. The designer should always be conscious that they have used interpolative methods to fill-in absent data points to create the surface. As more data becomes available through test results, benchmarking activity or classical analysis, this should be used to update the models to refine the surface fidelity. The PFAL process is intended as a guide to early stage design when complete data is not available. It should be modified when more representative data becomes available.

The designer must remain an integral part of the interpretation process. The use of any computer optimisation methods runs the risk that we default to the ‘power of the computer’ and assume that the results obtained are correct and complete. It is tempting to assume that the result of a mathematical calculation defines a ‘perfect’ solution. The results of any calculation always need to be validated and checked for veracity. This is all the more important when the process involves limited data at an early design stage on a complex task. Expert judgement should be brought to bear on all final decisions of interpretation.

Current limitations in the PFAL model’s ability to interpolate points intermediate to known heuristic inputs and anchor points, provide an opportunity to develop the process further, particularly when combined with a move to a more automated process in a different modelling environment.

The proposed PFAL adaptive landscape process relies upon a degree of interpretation by the concept designer. Expert knowledge must be brought to bear on the selection of data and interpretation of surfaces. Through the designer interviews, it has been discovered that concept designers are high-level generalists rather than detail mathematical modellers. They have a desire to concentrate their efforts in thinking about design options and weighing up alternative product considerations. Concept designers want to minimise the time that they spend on mathematical analysis and the need to learn complex modelling approaches, preferring to weight options and concentrate on the creation of configuration layouts - which is essentially a visual, spacial activity, rather than a mathematical analysis.

The design decision process as laid out in this research project, is currently quite manual. It relies of a series of stages, using several different software platforms. This is both time consuming to apply and a potential hindrance to the designer in performing concept evaluation work, where the process may start to distract from the core design activity. Automation of some of the tasks will allow concept designers to focus on weighing options rather than performing data analysis.

Another method of reducing the analysis burden and removing some of the manual interpretation is to generate surface shapes that are easier to interrogate for numerical values using simple geometric analysis and avoiding the need for complex surface modelling. Options for alternative surface representations are explored in Appendix C. Approximating surface profiles using Euclidean geometry will retain the essential components of the surface, such as peak position, fitness height, relative surface plateau, etc., whilst significantly reducing the analysis task. As the 3D surface generation is an averaged interpolation between sparse points in the first instance, there is no great loss of fidelity to the original data. If a more nuanced assessment of part of a surface is required, this should be a prompt to gather more detail for that area through further benchmark or detail classical analysis approaches. Indeed, there could be an argument that a surface based on sparse points may appear to be more representative than it is in reality. This could lead to a false sense of confidence in how accurately the surface represents possible feasible solutions. A simplified geometric surface representation might go some way to visually remind the designer that these surfaces will only ever be a relatively crude estimates of limited data, intended to aid design thinking and option selection. They should not be considered analytically robust.

5.4 Future Developments

The use of adaptive landscapes in presenting a fitness profile for concept design choice has great potential. The technique of being able to visually assess trade-offs between design parameters and be able to understand the impacts on their fitness in the operating environment for which they are intended, provides the concept designer with a means of not only selecting a feasible design point, but also being able to see its sensitivity to changes in that environment. The adaptive landscape shows product developers the limits to suitability for the design configurations and how robust they are to variation.

Modified landscapes enable limitations to be set on the purely mathematical interpretation of surface form. This means that the product developers can incorporate their own knowledge of future changes to be built into the model. These may be new areas of feasibility made possible by advances in materials and technologies that increase fitness in an area of the map that was previously infeasible; or it may be in restricting an area that may be impacted by legislation changes by reducing fitness to reflect that the zone is now restricted for consideration as a design choice.

The plateau, flooded adaptive landscape encompasses limits for consideration by providing a clear demarcation of fitness values that are not acceptable and a plateau of values that satisfice the requirements of the design. The benefit of the plateau is that it moves the designers away from over optimising the design to a point where it adds no more functional value, but starts to limit flexibility in trade-offs against other attributes.

This study has concentrated on the problem of concept design in IC engines. These have been chosen as they are a good exemplar of a high-volume product that incurs high capital expenditure and is subject to changing product requirements over its production lifetime. Other strategies to product change and requirements to adjust product geometry over a production life may be adopted for those categories of product that do not meet this criterion - see section 1.1 Thesis Introduction. For products with a short production life, or where dedicated production equipment is not required, a strategy of flexible or disposable equipment investments may be sufficient to avoid issues of building geometric change capacity into manufacturing equipment. There are however, many instances that replicate the constraints of IC engines. These include other aspects of automotive production, such as car and truck body production or gearbox and axle manufacture. Tractor or other specialist vehicle manufacturing also falls into this category. Certain types of higher volume production of aircraft and shipbuilding that use similar designs but with variation, would also fit the need for adaptability to uncertain future requirements using existing investments in capital equipment.

The PFAL process could be explored further in being applied to other industries and types of production environment. It is a relatively quick and easy process to apply and the activity of defining feasible design space and considering fitness for purpose across that space would benefit most types of product lifecycle planning, even if the actual needs of building in flexibility are relatively low.

Although relatively easy to apply, the PFAL process used in this study was quite manual and so could be improved through automation of some of the calculation tasks. This would also make evaluation of the dynamics of landscape changes easier.

5.4.1 Development of an Automated Decision Support Tool

The purpose of this research study was to develop the thesis of adaptive landscapes as applied to the concept design phase of engine programs. A simplified tool was created to test the generation of suitable landscapes that can be used for visualisation and exploration of engine architecture configuration geometry. The simplified surface model (SSM) was created to allow quick creation of representative surfaces from limited sparse data using the PFAL process.

The application of the adaptive landscape process is currently completed using a mix of models running averaging smoothing algorithms and manual adjustments based on designer experience. The process has proven to be effective in providing designers with perspectives on design space options and the limitations for geometric growth for selected parameter pairs. A next logical stage would be to automate some of the manual stages and to build in an expert system approach through development of an integrated decision support tool. This moves away from the aim of a tool that relies only on ubiquitous software, to a more dedicated package. This could have the advantage that it integrates expert knowledge from experienced designers into the analysis process and relies less on manual manipulation.

As discussed in section 2.2.4 Engine Lifecycles, concept design for new engines is an infrequent activity. Even if an engineer has been through the process before it may have been many years since they last needed to consider all of the factors required for a new engine. Their own personal database of benchmark information may be limited. Being able to get guidance from an expert system would allow the gradual development of best practice that could be shared across the designer community.

Automation of the mathematical tasks used to generate surfaces, interpolate values and display options is beyond the scope of this research project. Creating an automated process, particularly one that involved surface interrogation, is an exercise in computer science. It therefore needs to be undertaken as a coding activity to capture the design process and the generation of adaptive landscapes. Much could be done with creating a work-flow of input data points for the sparse set and output of the adaptive landscapes in a visual form that allows easy interrogation of specific parameter coordinates.

A future research activity could be to refine the data entry and analysis by building these geometry models into a parametric 3D environment as an automated code. Sparse data points could be entered and standardised geometries selected to best represent the surface. These could be combined for more complex surfaces, resulting in a merged geometry - see Appendix C on Alternative Simple Landscapes for examples of surface representation alternatives. This merged surface would be amenable to interrogation to calculate any given point over the combined surface by selecting parameter coordinates for the attributes required and determining the calculated fitness value at that specific coordinate pair.

It could be envisaged that types of expected surface could be defined as a menu of options e.g. saddle-back surface, Pareto frontier, etc. Sparse data could be entered into a system that matched these values to an assumed surface shape based on the expert knowledge of the user. Parameter limitations could be input such as absolute cut-offs, plateau ranges and fitness values Representative adaptive landscape could then be generated. Finally, this landscape could be used for the evaluation of concept options.

A further refinement of an automated system might be tracking parameter selection across several adaptive landscapes to highlight interactions in multiple dimensions between parameters. This could be applied to trading off physical geometry options such as package size, mass or key 5C dimensions against functional performance in the areas of power output, emissions and fuel economy. Final analysis of the parameter or attribute values would still require the expert interpretation of the concept designer, as the fitness surface provides only one of the inputs into the concept configuration decision making process.

5.4.2 Dynamic Landscape Modelling

The adaptive landscape is continually shifting. As the landscape is a reflection of a complex interaction of many factors that affect an entities ability to survive, it needs to be able to replicate the shifts in fitness peaks over time (Watson & Ebner 2014). An area that represents a fitness peak is the outcome of the influence of many attributes beyond the two used to map out the relationship under consideration. In essence, the adaptive landscape shows change in attribute values, but only for the two X and Y axes (attribute At_x and At_y). All other attributes are considered fixed. To gain a full picture of the interaction of attributes a range of landscape maps should be considered as a set.

As the other attributes not mapped by any particular adaptive landscape change, the values and relationships of the adaptive landscape may shift. For example, a map may show a relationship between engine performance and weight of an engine, assuming all engines are naturally aspirated. A separate map may be used for pressure-charged engines, such as turbocharged or supercharged units. If a new technology is developed to enhance the breathing of engines that does not neatly fit into either category, say a pulse charging system, then the values of the fitness peaks may change in magnitude and/or position on the landscape. Care should always be taken when evaluating the landscapes to fully understand what is not shown explicitly i.e. the assumed fixed attributes not directly represented by At_x and At_y.

Drift in fitness landscapes will occur over time due to developments in materials, manufacturing and design. An example of how a landscape fitness value might adjust is shown in Figure 103. This is from a technical paper on the design of a new Nissan engine (Doi, et al. 1994). A range of benchmark engines generate a fitness island with a defined boundary, for engine power versus mass. Within this island representative competitor engines are shown. Several design attributes are highlighted to better understand the effect of a third and fourth attribute, namely cylinder block material (Iron vs aluminium), which will affect mass, and configuration (in-line vs vee), which will affect mass and bore/stroke limits.

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Figure 103 Nissan Engine Benchmarks. Doi, Kimura, Murata & Ohki 1994.

The new Nissan engine VQ30DE is shown relative to the competitor product, including its position relative to the previous version of the Nissan VQ engine that it replaces. Other attributes of the new engine design were shown in the same paper on different comparative maps. Figure 104 shows specific packaging constraints with the new engine for different classes of vehicle. This diagram illustrates categorisation of map areas (sub-compact, compact and intermediate) together with the performance of the VQ engine with its competitors. This illustrates the movement of the value position with the new design.

Figure 104 Nissan Package Benchmarking. Doi, Kimura, Murata & Ohki 1994.

These landscape dynamics can be dealt with by several approaches:

Update Maps - Adaptive landscape maps should be updated to reflect the latest developments in the attributes under consideration, whether these are competitor data information becoming available, new technology developments in the field or modelling of design options that may be proven feasible through analysis even if they are not current in the marketplace. This is likely to be the most common way of keeping up with dynamic changes as the use of adaptive landscape analysis is episodic in nature, as new concept design activities are a relatively infrequent activity.

Time series Maps - If a particular trend in fitness peaks is of interest, a time series of related maps might be generated. This would be of use in assessing historical trends and looking at the influence of particular external factors such as the introduction of legislation or other driving constraints. Apart from being of historical interest, this may prove beneficial for projecting out the rate, direction and ultimate limits to attribute changes. For rapidly adjusting landscape dynamics it would be of benefit to keep a close watch on trending shifts in fitness peaks to better communicate with stakeholders how solution sets that were satisfactory in the recent past may not be viable in the near future. When needing to persuade stakeholders of the justification for investment in new product, it can be particularly helpful to show the changing landscape that is driving the desire for new product configurations or features.

Dynamic Modelling - For a very rapidly changing environment, it may prove useful to have a dynamic model created to show more complex shifts in the landscape profile. This has been done in the biological field to explain evolutionary processes (Richter 2014, Watson & Ebner 2014). The rate of peak fitness change in engine design is generally too slow to warrant a dynamic model being necessary, but as there has recently been a burst of activity around degrees of hybridisation and novel powertrain configurations for better integration with driveline systems, it may prove to be an area worth exploring for engine layouts.

Beyond the use of adaptive landscapes, there are opportunities for applying biological and evolutionary analogy to dynamic business and manufacturing environments, as discussed in section 2.3 Application of Biological Models. These approaches provide a means of better understanding dynamic interactions of complex systems, as well as modelling scenarios of change management to optimize resource utilization over projected lifecycles.

5.5 Conclusions and Recommendations Summary

This chapter has drawn the conclusions of the research study together and summarised the benefits and limitations of applying PFAL modelling to new engine concept design. The aim of the study was to develop a concept design decision support tool to enable change resilience over product manufacturing lifetimes. This was achieved through the application of a biological analogy of adaptive landscapes to incorporate a satisficing philosophy in reaching acceptable trade-offs between attributes of key dimensions in the early stages of an engine concept design. Through this process it was hoped to raise the awareness of the consequences of key dimension selection in a concept design, on its ability to limit future change for capital intensive products. A simple process was sought that would produce visual representations to engage a wider range of decision stakeholders who may not be technical experts.

The PFAL process has shown some benefit in aiding the concept design thinking stage of a new engine program. Its principal benefits lie in the way that it draws the designer's attention to planning the full lifecycle consideration of key dimensions into an early stage of the design. This helps the designer avoid setting key dimensions that may limit options for future expansion or change of the product over its production life. Past history shows that high investment, long life products tend to need to evolve in form, whilst continuing to utilise as much of the current investment in plant and equipment as possible. The PFAL (Plateau, Flooded Adaptive Landscape) process was developed and this was applied to sample engine designs. It proved effective in being able to model the adaptive surfaces and aid in decision making process. The process has merit and should be developed further as a decision support tool to aid trade-off decision making under uncertainty, with sparse data.

Potential limits to the approach are highlighted, as well as opportunities to further develop the tool. This chapter makes a recommendation that the tool be further developed to improve ease of use and encourage wider application to similar areas of analysis. It is recommended that the PFAL process be further developed, to prepare it for a field trial with engines designers. Consideration should be given for a stand-alone tool that does not require specialist software or training to use. This may be in the form of a software application that has a simple user interface to draw in data from an input spreadsheet and perform the PFAL calculations in the background, so that the engine designer does not have to perform manual operations on the data. A simplified user interface should be developed making use of sliders and intuitive controls to set the study parameters. Output would be visual representations of the generated adaptive landscapes that could be exported for dissemination to other stakeholders.

It is anticipated the tool might have wider interest in other fields and certainly applied to the concept design of other manufactured products. It satisfies the need to show a representation of relationships using sparse data in a visual form and has wider applicability than just concept design decision making. There is potential for opportunities for application outside the topic area explored in this study.

Some options for investigation of alternative topologies of surface definition, as well as recommending a review of alternative smoothing algorithms to suit different needs is included in the appendices for further consideration.

Appendices

Appendix A - Data Sources

The information used in the research study came from a number of sources. Wherever possible, information was cross-referenced to validate the numbers or checked against published information from peer reviewed publications. The author has over 30 years' experience working in the automotive and consulting industries on the design and development of engines. This enabled information to be 'sense checked' against the author's knowledge of the concept design and lifecycle planning of engines in industry. It is recognised that care needs to be taken to avoid 'confirmation bias', so the author's experience was used as a final check and not the sole source of information for any given aspect of the study.

Published information was used for contextual information and background theory of new product development, engines technologies, lifecycle planning and biological evolutionary theory. Specific aspects of the study such as cellular automata neighbourhood modelling algorithms, Norton-Bass and technology adoption models, adaptive landscapes and use of heuristics in decision making were explored through journal databases. The Aston University and University of Wisconsin - Madison academic library paper and journal databases provided the majority of the academic research. Scopus and Web of Science were the two primary publisher databases searched, supplemented by the Society of Automotive Engineers Mobius database and specialist publishers' sites, such as the Design Council, institute websites and thesis repositories such as Ethos (British Library) and US thesis repository via ProQuest.

Academic texts, especially related to biological modelling of morphology, provided the author with grounding in the theory of body forms and biological modelling. These have been cited where appropriate in support of the application of theory to the research methodology.

Information from internal company reports concerning design benchmarking activity, engine cost studies and engine strategic planning were available for reference through contacts in industry and the authors own notes of general trends and benchmarks in these areas, gained over a career in the industry. Confidentiality was respected and only historical data was accessed as exemplar instances from which generic results could be drawn.

Interviews and surveys were carried out with experts in the field of engine design and development and particularly concept configuration generation.

Interviewee Profiles

The interviews were conducted with experienced engineers and new product development experts in the engines industry. Contacts were made through the authors former colleagues in the engines industry. Interviews were conducted either in person or by phone for 1-2 hours per interviewee.

Semi-structured questions were asked to obtain contextual information for the engine concept design process. The interview process was left open so that areas of interest could be explored during the interview. Question categories included:

Concept Design Process

1. Explain the process of engine concept design in your experience.
2. What are the stages of the process and who is involved.
3. How are design trade-offs made during the concept process.
4. At what stage is the concept architecture frozen.
5. How important is quantitative analysis vs qualitative personal experience in engine design choices.
6. Who makes design trade-off decisions for concept architecture.
7. What is typical project performance for engine programs for time (Launch) and cost.
8. Do you use heuristics in engine design. Where is heuristic data obtained?
9. How is benchmarking used in concept design (competitor data).
10. How do you determine future needs in engine specifications.

Design Lifecycle

1. What are the typical lifecycles for engines in your experience.
2. How long are engine in production (families and variants).
3. What are the drivers for change in engine designs.
4. How is end of life determined. Is end of life planned at the concept stage.
5. How long is expected lifecycle of engines. How is this determined.
6. Describe ramp-up and ramp-down cycles for engine production lifecycles.
7. What are typical time periods for ramp up/down to occur.
8. For engines your experience what is expected vs actual production life.

Engine Business Case

1. How is the business case for a new engine determined. How are assumption calculated.
2. What are typical hurdle rates of return for engine program investments.
3. For projects in your experience, what cost overruns for investments are encountered.
4. What is expected production life of engine manufacturing equipment.
5. How much consideration is given to equipment reuse.
6. What are the volume assumptions on dedicated vs flexible equipment. How does this effect engine design?

Background on interviewees experience is in Table A-1 below:

Designation	Role	Years' Experience	Engine Concept Projects	Company	Location
A	Designer	30	8	Consultant	UK
B	Project	21	6	Consultant	UK
C	Project	18	6	OEM	USA
D	Designer	14	4	Consultant	China
E	Designer	6	2	Consultant	China
F	Marketeer	14	4	OEM	UK
G	Marketeer	12	2	OEM	USA
H	Project	23	5	OEM	USA
I	Designer	18	4	OEM	USA
J	Designer	26	6	Consultant	UK
K	Project	15	3	OEM	USA
L	Designer	17	4	OEM	USA
M	Marketeer	12	5	OEM	USA
N	Project	16	5	Consultant	China
O	Marketeer	8	3	OEM	USA
P	Designer	8	4	OEM	USA
Q	Designer	14	3	Consultant	UK
R	Designer	17	4	Consultant	UK
S	Project	17	6	Consultant	UK

Table A- 1 Interviewee Profiles

Appendix B - Possible Types of Data Error

Secondary data has been used throughout the study to understand the size, scope and segmentation of the engines markets, establish trends in technologies and their adoption, to determine the pace of change in engines designs and a host of other indices that have informed the context under which the research has been undertaken.

With data being used from a number of different sources it has been important to have a structured process to evaluate the validity and reliability of the information used. Several best practice criteria have been used in reviewing potential sources of information and making selections of which data to include in the analysis.

Source: The original source of the data inputs has been considered. This includes whether the data has gone through interpretation by a third party. A number of studies, research reports and publications use summary data, charts and tables from other publications. Wherever possible, original sources were used.

Publisher: Who has published the information is important in establishing potential bias. Some of the materials consulted as part of the study were produced, essentially, as marketing or publicity materials by OEM organisations, tier 1 supplier groups or government entities. Each of these sources has their own agenda, even if it is one with the best of intentions and they have clearly tried to be as objective as possible. In reviewing data, "What are the intentions of the publisher?" was asked to ensure that unconscious bias was accounted for in how the data was filtered and presented.

Intentional Bias: Occasionally, information may be presented with a more overt intention to influence the readers opinions. Most notably sectors with vested interests such as the oil & gas industry or independent environmental advocacy and pressure groups, may have a particular point that they wish to make with their presentation of data. This is more likely to result in selective use of information and in extreme cases to misrepresentation. Considering the source and intent enabled due weight to be applied to the data provided. Cross checking and where possible, tracking data used to original sources, mitigated most of the effects of this type of bias.

Data issues encountered during the study included:

1. Incomplete Data - Databases of information are often incomplete. The wider the scope of the database, the more likely that data will be incomplete. An example of this is the global engines data for markets and production. Several 'world' engines databases were consulted during the course of this study - see Appendix A. All were found to have a strong bias to the markets for which they were produced, whether USA, Europe or Japan. All made attempts at having a global coverage but were more of less successful in this regard. By comparing similar data from different sources and markets, it was possible to cross-check data entries and combine datasets from multiple sources.

2. Duplicates - Data entries can be duplicated, with 'double counting' of production volumes, costs or other comparative data. This was particularly noticeable when data was combined from several different sources, where those providing the raw data may have made different interpretations about scope and what to include. An example of this is in engine program or investment costs - Were engineering and tooling costs separated out or combined into a total figure? Checking published data entries against known figures from projects on which the author had personal experience allowed for some of the assumptions to be teased out of datasets. There were limitations on how far this could assist understanding of assumptions and errors may remain in the data used.

3. Transcription errors - Data has been transferred from printed sources, into databases, through an analysis and on to publication. At each of these stages, data entry errors can occur in transcription of data and results. Even in high cost datasets purchased for the study or published materials from reputable sources, it was noted that clear transcription errors had occurred. With datasets containing many thousands of lines of data covering hundreds of engines, it was inevitable that errors may appear. Where these were spotted, they were corrected for in the analysis.

4. Relevance (extraneous data) - Data is often prepared for a diverse market of users, who may have different interests and requirements. In the case of automotive engines, the primary focus for many users of the data is at a vehicle level. This meant filtering and combining data points to reduce the potential for duplicates and to make handling datasets easier.

5. Accuracy - All datasets will contain errors of accuracy. The data that is present may be inaccurate due to poor entry or rounding errors. In most cases the level of accuracy for adaptive landscapes is not critical, as the information is being used to create an impression of the feasible design space rather than for precise analysis.

Every effort was made to correct or compensate for errors in data but it is inevitable that in such large datasets some errors may remain. As the analysis uses combined data to obtain a generalised adaptive landscape for option exploration, it is unlikely that any minor remaining errors will be significant or substantively effect the analysis conducted and the conclusions reached.

Appendix C - PFAL Process Detail

The process of building a plateau, flooded adaptive landscape and applying it to decision making in concept design is completed in a series of stages. Figure C-1 shows the process steps to complete the process including key inputs.

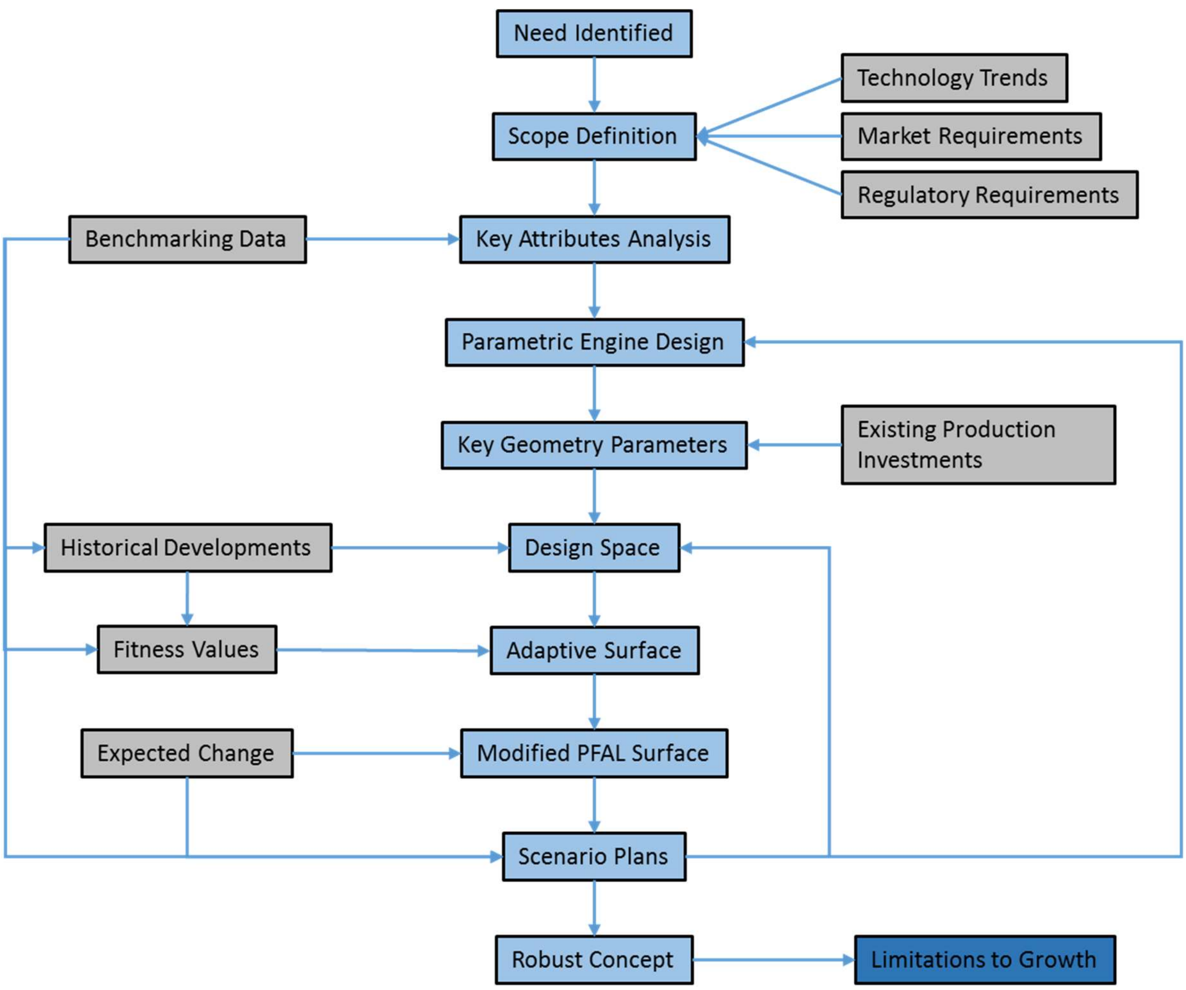

Figure C- 1 PFAL Stages

Market Need - The driver for change to an existing family of engines, or to create a new family of engines is identified. This activity is led by the marketing function within most organisations and draws on a number of sources to identify when a market need arises. This may be driven by market opportunity, formed through business strategy e.g. entering new territories or sectors, made necessary by changes in regulatory compliance or other factors. In order to apply appropriate fitness values to attributes at later stages of the MAL process, it is important that a clear and agreed change need is defined.

Scope Definition - The scope of the project requirements must be defined and agreed by stakeholders. Inputs will be required from multiple functional areas of the business and should include market requirements (beyond the original driver for the change), trends in technologies, materials and manufacturing; as well as a comprehensive review of the expected regulatory environment. The initial need was prompted by current or near-term requirements, whereas this scope definition should consider the potential changes in these aspects that will affect the product specification over its entire production life. Lifecycle planning considerations are therefore introduced into the process at the earliest stages.

Key Attribute Analysis - The key performance attributes of the product family, over it expected production life, are defined. These will include emissions performance, fuel economy, power and torque output characteristics, as well as dimensional requirements such as package size and weight. The attributes will feed into the selection of key geometries. Benchmarking data of competitor products and existing company product will be used to establish feasible designs. This should be tempered by consideration of future trends and not just current, known data.

Parametric Engine Design - The first configuration of the engine can now be laid down, such as cylinder number and arrangement, displacement, valvetrain type, etc. This is a starting point for further analysis and will not become fixed until verified through the rest of the adaptive design process. At this stage, several alternative designs may be taken forward for comparative analysis, such as variants of number of cylinders, vee or inline configurations. Using parametric modelling, the major geometry of the engine concepts under consideration will be assessed. This is the first detail analysis and provides indications of relationships between geometry, especially constraining dimensions for packaging.

Key Geometry Parameters - The Key geometric relationships that need to be modelled with adaptive landscapes will be identified by the engine parametric model.

Existing investments and constraints of manufacturing equipment will be factored into the geometric parameters that can be changed. The parameters with the greatest constraint, through production equipment limitations or that have the greatest cascading effect of engine design attributes will be identified for detail analysis in the design space. As small a set of parameter pairs as possible should be use, to ease trade-offs for multiple criteria. A set of design space adaptive landscapes will be identified as having the most impact on the overall design.

Design Space - A design space is then created for each parameter pair. The range of this design space will be determined by benchmark data, historical engine growth patterns and the values range of geometric parameters that wish to be evaluated. The design space may need to be revisited through iteration if updated information becomes available from further development of the concept layouts.

Adaptive Surface - An adaptive surface is generated from known feasible data points and projections or simulations of calculated feasible zones. This forms the fixed points of the landscape based on fitness values calculated from relative spacing of fitness's from zero (0) to one (1) representing known infeasible points to maximal fitness points. The fitness selection algorithm applies a weighted averaging to distribute fitness values from the optimum location. Applying von Neumann neighbourhood calculations in the cellular automata design space fills in the interpolated landscape surface between known points. This defines the shape of the landscape and its relational links to fixed points, that can be further adjusted by manual moderation.

Modified Adaptive Surface - The adaptive landscape can now be modified by placing limits of edge conditions (Pareto frontiers), introducing fixed anchor points or opening up previously infeasible zones due to known future development in technologies that will adjust fitness values. At this stage, application of plateau functions and flooded zones can be applied to better represent adaptive plateau of equal fitness and less optimal, but still feasible surfaces below the plateau. Islands of equal fitness may now appear in the design space map. These manipulations represent known or expected changes in fitness over the manufacturing life of the engine family.

Scenario Planning - From historical data and expected changes identified in constraints and drivers of change, scenarios of future engine geometry change can be modelled. These can be assessed against the limits to growth shown by the PFAL maps. Change scenarios will need to the checked across each of the parameter pair MAL surfaces produced. If unacceptable parameter values are indicated or the limits to growth are considered unacceptable, then iteration around design configurations may be required. The limiting information can be fed back into the parametric design process to make design adjustments.

Robust Concept Design - When a concept design satisfices all of the requirements and provides a robust layout for expected future changes to the engine architecture, the concept can be frozen. The concept can then be taken forward for refinement and development, including the building of prototype hardware with confidence in future expenditures being on the right track. The limitations for growth and by implication end of product life, are now defined. This allows advance planning for replacement product when the current design family has reached its limits.

PFAL Process Modelling Stages

The spreadsheet model developed for generating adaptive landscapes uses input data from benchmarking. Figure C-2 shows the benchmark data sheet. Selected values are used to calculate the range of design parameters to be modelled. These may be manually adjusted if a broader range is to be considered. The sheet divides the values into an even distribution across the 20x20 matrix of the design space. Standard deviations and mean values are calculated from the parameter ranges, for use in modelling fitness values.

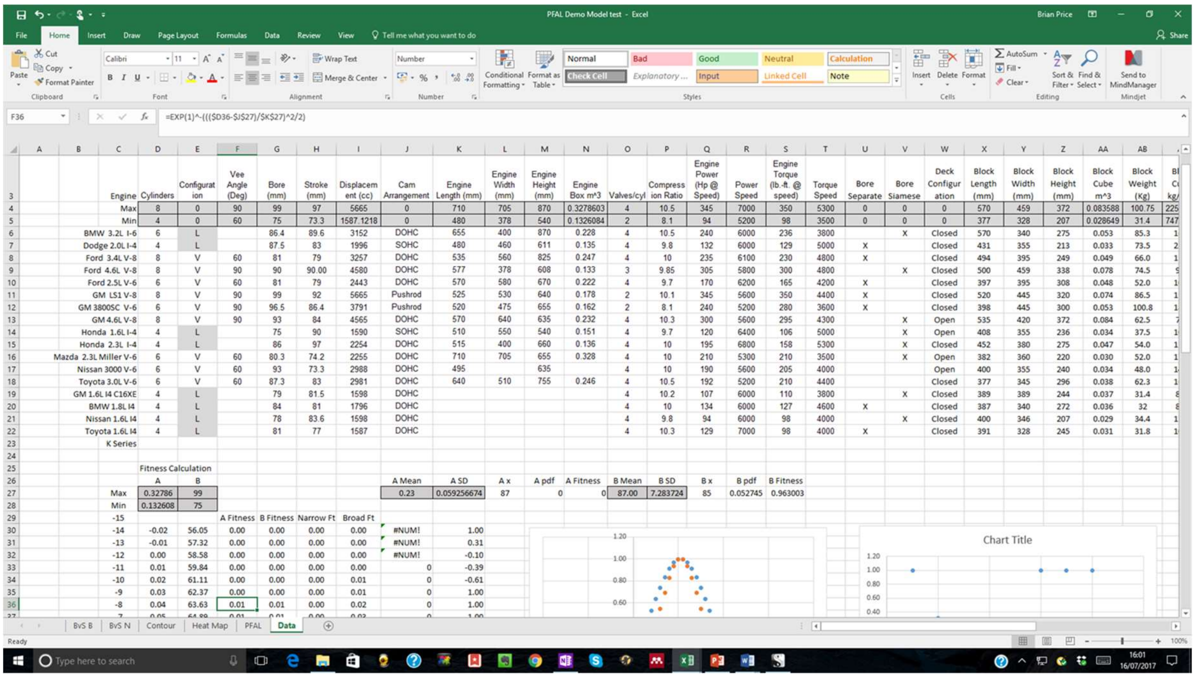

Figure C- 2 Benchmark Data Inputs

The analysis is separated onto separate tabbed sheets to aid display of the information. The design space tab is shown in Figure C-3. This contains the columns for the parameters calculated in the benchmark input sheet, automatically transferred from that sheet. Fitness values are calculated based on the fitness formula shown in section 3.6.2 Selection of Fitness Values. The design space has the known data points entered in the appropriate parameter location. The sheet has been set up with conditional formatting so that the cells are colour coded to the fitness value calculated. The darker the colour, the higher the fitness value. Figure C-3 shows that the fixed cells and their near neighbours have turned dark blue. As the 3D MAL surface representation has not yet calculated, it is shown as a flat landscape.

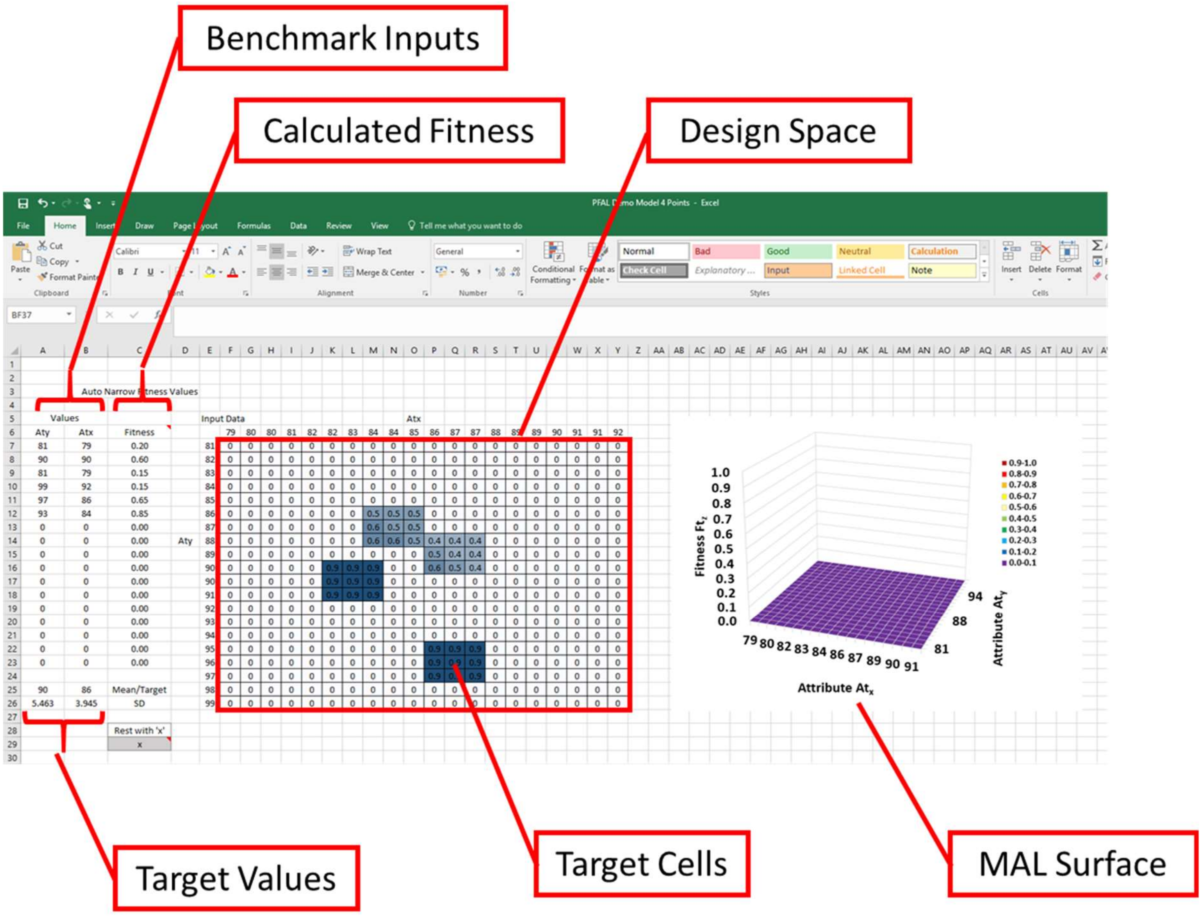

Figure C- 3 Design Space Tab

The adaptive landscape model iterates to a stable solution using the von Neumann neighbourhood algorithm. Figure C-4 shows intermediate stages of the iteration process. In reality, there are 30,000-50,000 iterations before the surface converges to a stand condition. For simplicity, only four intermediate stages are shown. The first stage shows the dominance of the target fixed values, with minimal surface interpolation. The final stage shows a converged surface that represents the final landscape model. The two images between show intermediate steps of the surface form. Note that the calculations start from an anchor plane, so the landscape surface appears to ‘rise’ to fill in between the fixed benchmark points.

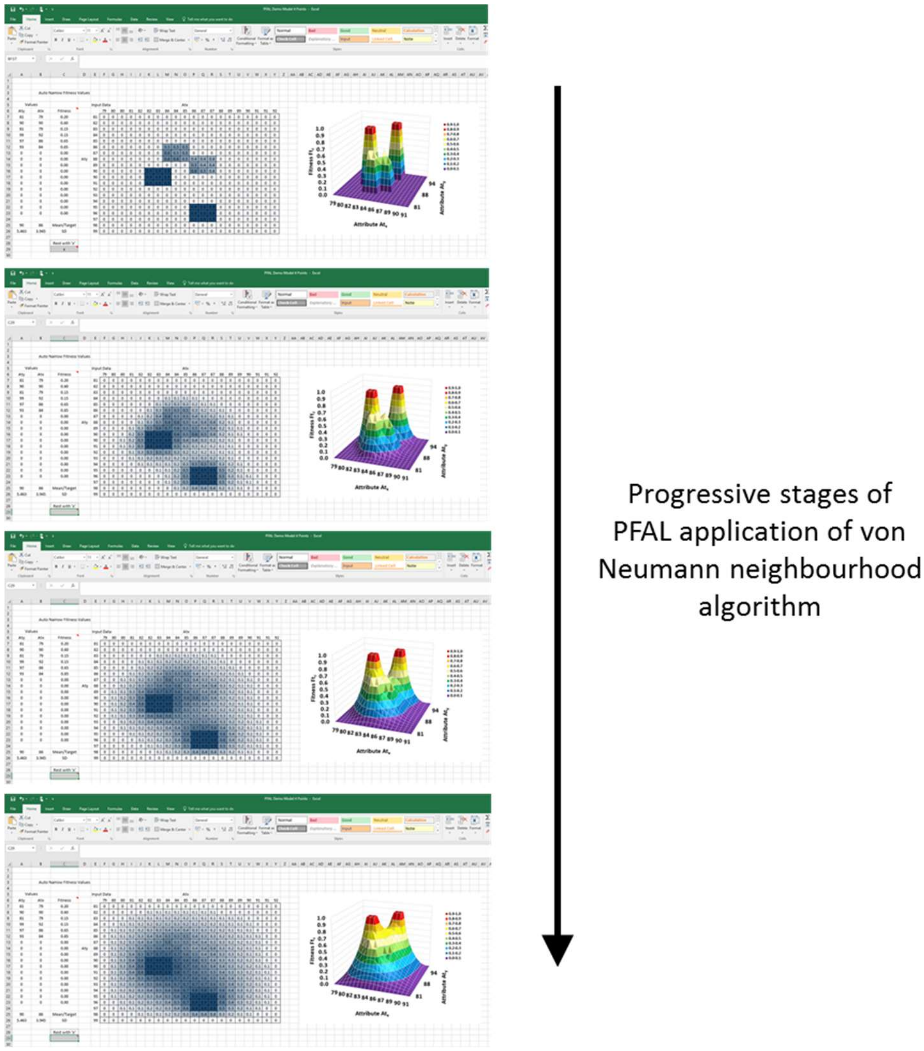

Figure C- 4 Adaptive Landscape Generation Stages

This landscape is not yet modified. PFAL limits are applied to produce the final surfaces used for evaluation and concept geometry selection. Individual tabs show 3D landscape views, contour plots views and heat map views. There is also an alternative block plot simplified landscape view, as discussed below. Each tab contains four views: 1) an unmodified landscape, 2) a plateau landscape, 3) a plateau landscape with flooded infeasible zones and finally 4) a PFAL landscape with a simplified intermediate zone. Figure C-5 shows a sample contour plot tab with the four views.

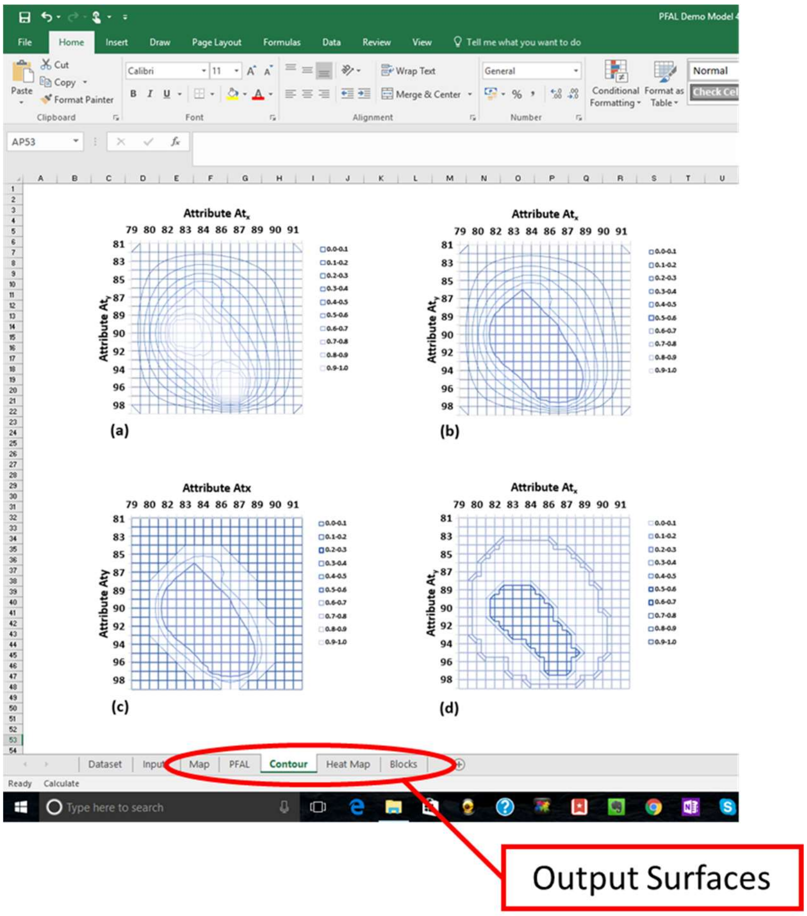

Figure C- 5 Contour Plot Tab

The adaptive landscapes produced are used to inform concept architecture key geometry selection as generated or they can be manually adjusted to take into account further moderation of parameter values from known constraints.

Alternative Simple Landscapes

Simplified adaptive landscapes may take several different forms to suit the needs to the concept designer. Each of these forms have their own relative merits and limitations.

Full Surface - The most nuanced surfaces can be generated using mathematical algorithms to generate 3D surfaces from available input data. A number of scientific data analysis packages such as SigmaPlot, NCSS, Origin Labs, XLStat and many others, provide curve fitting algorithms to interpolate between data points to generate a representative 3D surface. The subsequent surface form provides the concept designer with a good representation of the relationship between the design parameters chosen for analysis.

A disadvantage of this approach is that it relies on designers having access to specialist software and the necessary training to use it with a degree of ease and fluency. Interrogating the generated surfaces to extract relevant data that can be used in subsequent analysis is a relatively complex undertaking and beyond the capability of most engineers involved in the concept design process. The task moves from one of design layout to design analysis, which is a different skill set and usually done by other functions.

Simplified Columnar Surface - The full 3D surface can be represented by a series of columnar data that show the values of each cell on the landscape grid. Taking the data points directly from the cellular automata calculations, the column map provides easy interpolation on the level of defined grid points.

The bore/stroke ratio example shown earlier in Figure 90 has been replicated using a simplified geometry of cellular columns. This represents a series of unitary plateau of fitness values for each cell of the 20x20 modelling grid. As plateau and flooding algorithms are applied, fitness levels converge. The surface shown in Figure C-6a is a block depiction of the full surface. After application of the plateau algorithm a clear plateau emerges at 0.6 fitness value (Figure C-6b). The addition of the flooded plane at 0.3 fitness value, segregates the three zones of the landscape model with some degree of gradation in the sub-optimal zone still evident, despite the simplified nature of the model. A final stage fitness value merge combines intermediate surface values between the optimal plateau and flooded plane to 0.4, resulting in image (Figure C-6d). All of the surface values in the block models can be directly interpreted from cell values in Excel, negating the need for any intermediate surface calculation, with Figure C-6d reduced to one of three values for each cell defined by parameter pairs.

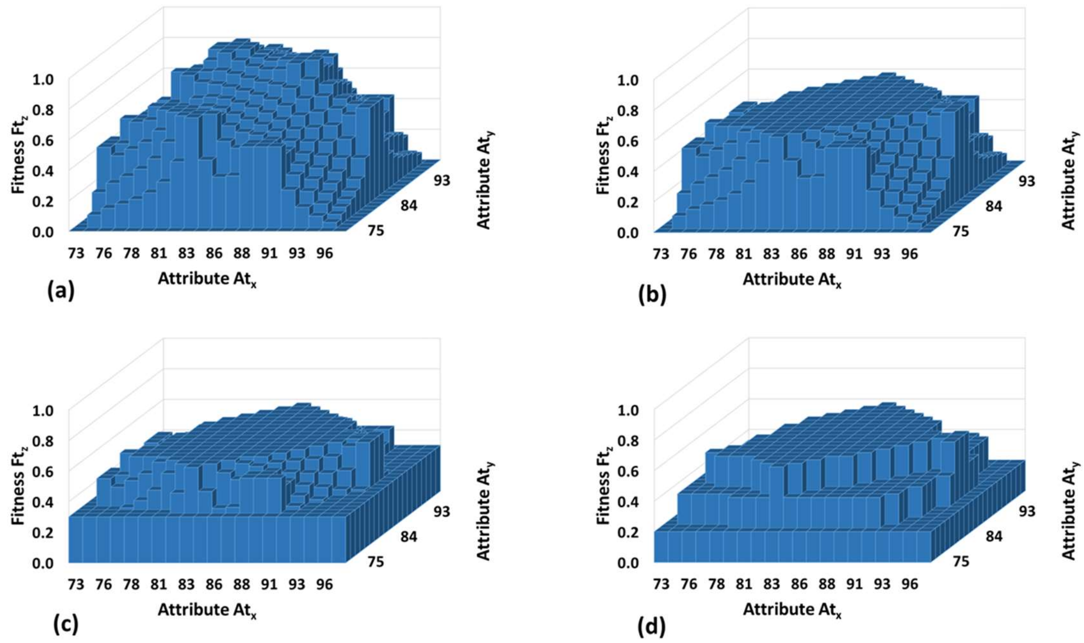

Figure C- 6 Columnar PFAL Representations

Simplified Shape Substitution - The concept of an adaptive landscape can be simplified further by using basic geometric shapes to replicate the surface required. The 3D surface can be replaced by a series of basic geometries that would allow easy generation and simplified interrogation for quantitative analysis. This basic geometry representation can be thought of as a pseudo-surface and is particularly useful in evaluating the sub-optimal surface between the optimal plateau and any flooded plane that might be applied. The full 3D surface may be represented by substitution of simplified shapes such as cones or cylinders. The advantage of these substitutes is that they reduce the surface to its essential form and are easier to interrogate to extract interpolated data points for further analysis. Using geometry calculation principles, fitness values of random, user selected parameter coordinates could be interpolated from the pseudo-surface. This eliminates the need for complex topology calculation, which would be beyond the modelling capability of generic calculation tools such as Excel.

By reducing the representation of the adaptive surface to the satisficing plateau we essentially end up with a cylinder for the definition of the adaptive landscape. A cylinder represents the adaptive plateau and the limits of the flooded plane but reduces the sub-optimal surface zone to a vertical wall. This shape representation allows for relatively straight forward modelling of the surface. More complex surfaces may be generated by combining several cylinders.

The varying heights of the cylinders indicate local satisficing plateau that are still acceptable to the concept designer. These may be necessary to explore as design parameters beyond those defined by the adaptive landscape may require compromise in parameter selection away from the optimal plateau cylinder.

The different plateau cylinders may have varying plateau areas determined by the particular constraints of the design. For example, a lower level of fitness often results in a greater degree of flexibility i.e. a larger plateau. Figure C-7 shows the substitution of a conical surface with a series of stacked cylinders for each level of fitness. Combining substituted fitness level cylinders for a more complex surface results in a contour value surface that will be familiar to geographers. Figure C-7 shows an overlay of the basic geometry cylindrical representation over a section of the 3D ideal surface, in this case with a family if five cylinders stacked to better match the profile of the adaptive surface. Each cylinder can be thought of as representing a contour of fixed elevation on the adaptive landscape. It can be seen that although this is an improvement on fidelity to the single cylinder, this representation makes several compromises to the extent of the plateau surface and may prove too crude for most applications.

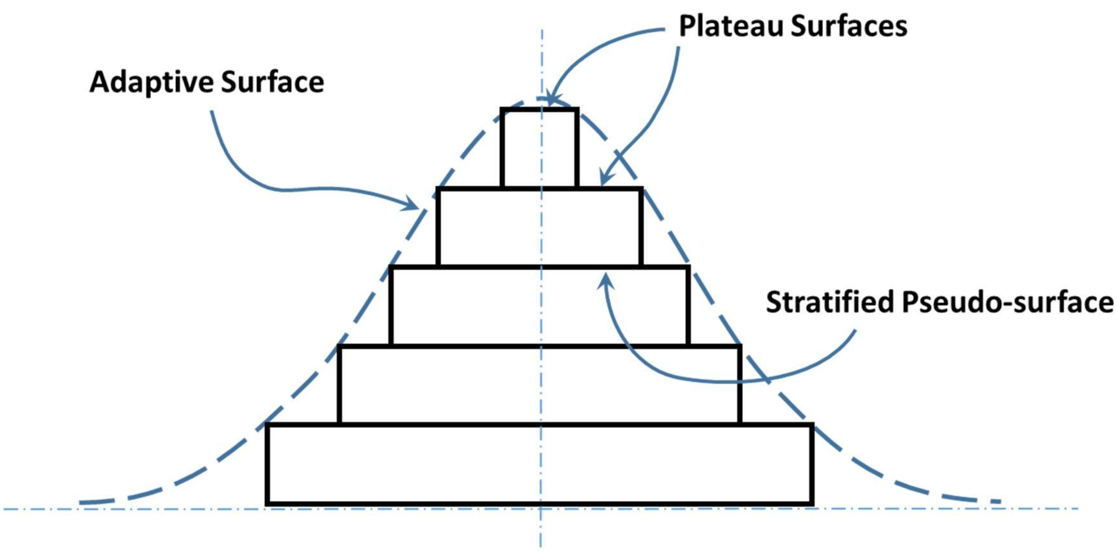

Figure C- 7 Stacked Cone Simplified Surface

Several basic shapes can be combined to generate a more complex representation of an adaptive landscape as shown in Figure C-8. In this instance, cylinders have been placed on the adaptive plane at coordinates that represent the location of fitness peaks. Fitness magnitude values are shown by the height of the cylinders above the plane. The diameter of each cylinder represents the extent of its adaptive plateau which may vary by location i.e. cylinders will be differing heights and diameters.

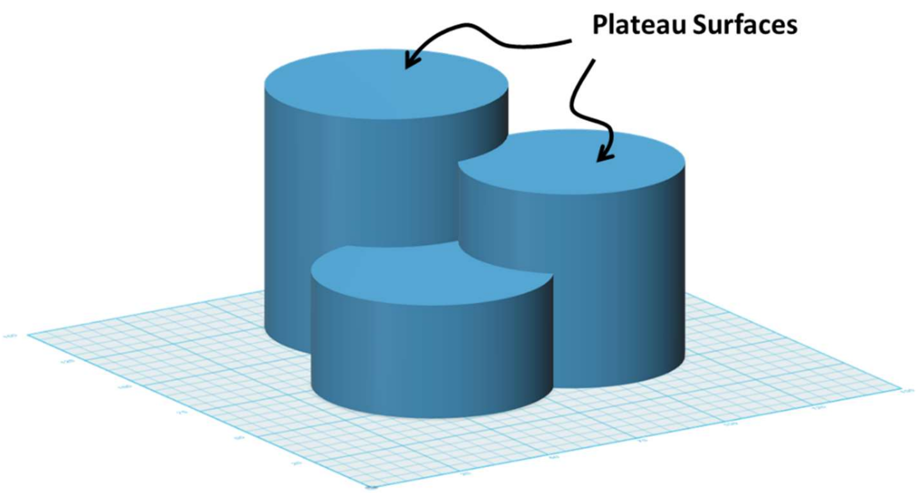

Figure C- 8 Cylinder Simplified Shapes

For a single point, sparse data set, one of the simplest forms might be a cone. A simple cone can be used to represent a peak value and base coverage (area of application of the parameter relationship). Several cones may be combined to represent more complex adaptive landscapes. A further refinement of the cone is to incorporate truncation to indicate the plateau of fitness to meet the requirements of satisficing the objective design criteria. A flooded plane can be introduced to cut off consideration of lower values of fitness.

The conical shape allows for a more faithful representation of the idealised surface for a single point dataset (Figure C-9a). The interpretation of the geometry is still relatively simplified compared with a surface generated from a 3D smoothing algorithm, but is allows more nuanced interrogation of sub-optimal points on the surface. Truncating the cone gives an optimal adaptive plateau (Figure C-9b), and the flooded plane can be represented by either an intersecting cylindrical shape at the base of the cone, or a vertically truncated section of the cones base (Figure C-9c). This simplified geometry is a good compromise between ease of analysis and fidelity to the idealised landscape. A further refinement of the alternative simplified geometries is to place a shallow domed surface on the truncated plateau (Figure C-9d). This gives an indication that although the truncated plateau has broadly similar values of fitness to allow for adaption there is are points on the plateau that might be more desirable as design targets. This draws the designer's choice on the plateau points away from edges, where there is less room for adaption before encountering a diminishing fitness value on the sub-optimal surface.

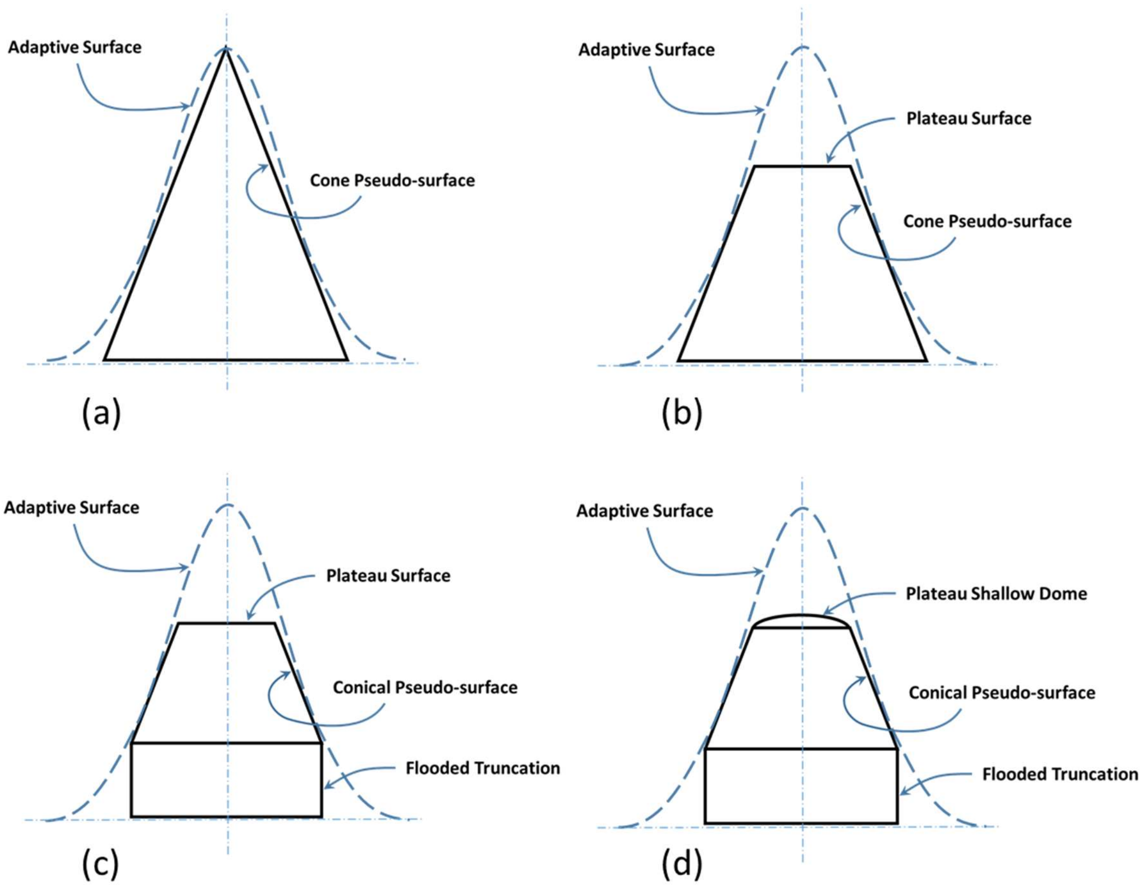

Figure C- 9 Simplified Conical Surfaces

A 3D model allows us to visualise these basic shapes on an adaptive plane. Figure C-10 shows a conical shape and a truncated conical surface that provide two alternative forms for individual peaks on the adaptive landscape. The advantage of using simplified shapes in this way, is in their ease of modelling and interrogation.

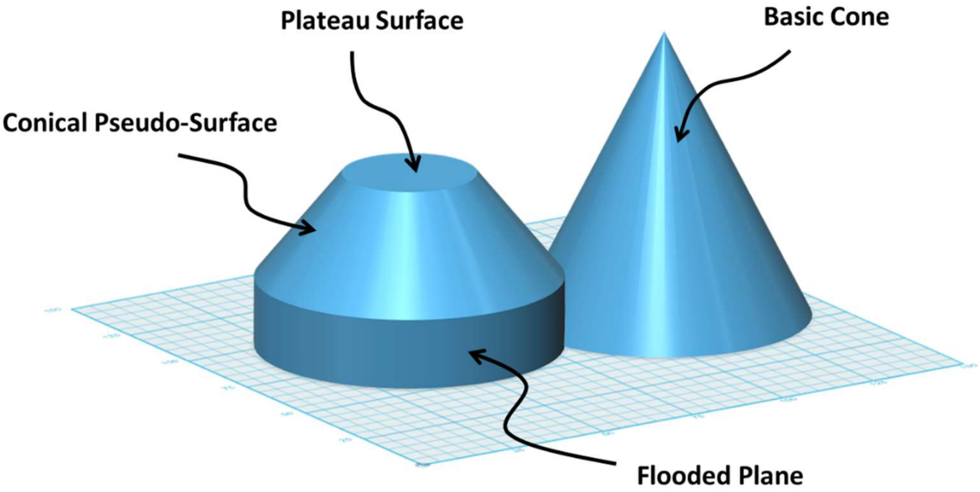

Figure C- 10 Simplified Shapes

The basic geometry shapes proposed above can be combined to replicate more complex landscape surfaces. This is particularly useful in showing the relative arrangement of multiple intermediate plateau levels across a landscape. A 3D rendering of the basic geometry shapes shows how they might appear if several simplified geometries were used to replicate a more complex surface with three peaks (Figure C-11). This gives us not only a visual representation of peak location, magnitude and extent, but also better indicates the surface shape of the terrain by use of sloped surfaces.

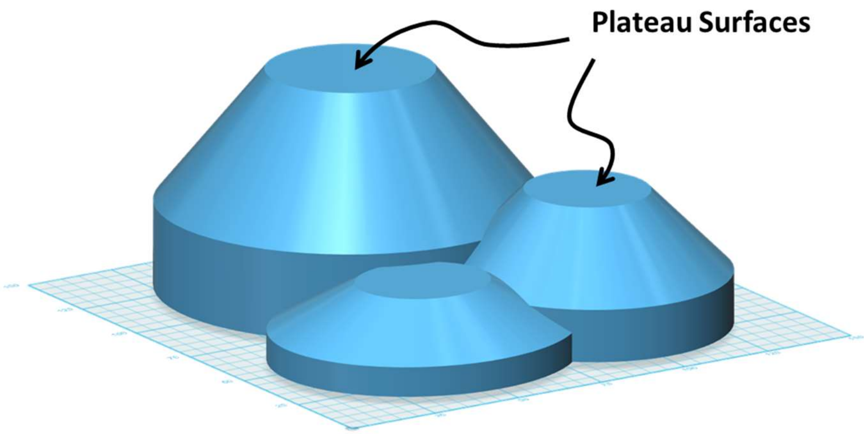

Figure C- 11 Combined, Simple Shape Surface

Further development of surface representation shapes is beyond the scope of this thesis. The needs of the concept designer, the tools available to model and interpret surfaces and the degree of accuracy required in representation will all factor into the choices of modelling method used. Further work can be conducted into assessing accuracy and ease of use of different surface representations as follow up research.

Modelling of Simplified Landscapes

Adaptive landscapes can be modelled as simplified topologies in order to reduce the complexity of the model and the need for specialist software for analysis. The adaptive surface can be generated from a sparse data set using the following procedure.

Step 1. Surface Generation. The adaptive landscape is generated from available sparse data to populate a parameter map. The data can be drawn from known benchmarking data points. These set the fixed parameter relationships between the product features under consideration. For example, emissions performance may be assessed against engine bore size based on data from parameter testing or secondary published materials.

In drawing up the adaptive surface, several sub-stages are performed:

Step 1a. Data gathering. Relevant information for fixed data points are selected. The concept designer needs to select the data from parameter characteristics that are well understood and relevant to the assessment being conducted. The designer’s expert knowledge plays an important part in ensuring appropriate parameter selection. With experience, the identification of key parameter comparisons will result in a set of standardised parameters that can be recommended to less experienced designers. Having a reduced set of parameter pairs used in repeated analyses allows for trends to be identified and comparative assessments to be made between designs. This creates a benchmark set of expected parameter behaviours and limits that build a collective body of knowledge for concept designers, either in a group or individual basis.

Step 1b. Fitness value. A fitness value can be attributed to parameter relationships, based on a number of criteria. These may be generated from any criteria set considered significant by the designer. The addition of a fitness value turns the parameter map into an adaptive landscape. Possible criteria for value attribution include:

Usage value (population) - Using the biological model of reproductive success as a criterion for selection, we can infer fitness of a parameter pair point from the 'population' of that pairing. The population may be defined from sales volumes, production figures, usage rates, or any other criteria that establishes popularity. A disadvantage of this method is that it is limited to what is available in current usage and does not cover non-current configurations.

Functional value - a third parameter linked to a functional attribute of the parameter pair may be used as a proxy for fitness. As an example, engine bore and stroke may be the parameters being considered for the adaptive landscape (X and Y axes), and engine package height might be the fitness parameter (Z axis).

Desired attribute - The concept designer may weigh the trade-off of a parameter pair based on a desired outcome. This requires a degree of understanding on the part of the designer, of the characteristics of the trade-offs possible between the pairs, and especially the limits to such trade-offs. An example of this might be engine weight and cost being considered for trade-off as paired parameters. For a particular application, say aerospace, engine mass will have a relatively high value, compared with cost. For an alternative application, such as agricultural or locomotive applications, not only might cost be of a more sensitive parameter, but it may even be desirable to have a certain minimum mass for stability and dynamics reasons (vehicle mass as a positive attribute).

The concept designer may therefore choose to use expert application knowledge to derive a set of weighted fitness values appropriate for the application under consideration. The important aspect here is that these have been carefully *considered* by the designer as part of the concept generation process.

Weighted map values - If data is available on a generic adaptive map population, weighted fitness values may be derived from centralised or Pareto frontier assessments of high value points. A benchmark subset of data can them be mapped to this generic surface to infer fitness values.

Step 1c. Probability distribution application. However the fitness values are established, we need a mechanism to create a future likely projection of outcomes. This ensures that accommodation is made for variable future values, rather than assuming exact replication of prior outcomes. A Monte Carlo analysis of fitness values can be run, based on criteria from prior data (expected range, dynamics of data, etc.). This results in a modified value set applied to the fixed data points.

Step 1d. Surface generation from fixed points. Once the fixed-point data with modified fitness values are entered into a parameter map, a simplified surface can be generated using an appropriate smoothing algorithm. At its simplest level, an averaging algorithm can be used to interpolate points between fixed parameter pairs.

Step 2. Surface Modification. Once the adaptive surface is generated, it can be modified to apply a truncated plateau and a flooded plane.

The truncated plateau establishes a ‘zone of goodness’ for the parameters being considered. This is an area of the adaptive landscape that satisfices the requirements under consideration. Any parameter pair of the plateau are considered equally effective in achieving the required design outcomes.

The flooded plane defines the areas of the adaptive landscape that are invalid design spaces and are not considered satisfactory solution sets for the concept design. These parameter pairs are discarded from consideration by the designer.

The landscape slope surface defines trade-offs in the parameter pairs of decreasing fitness and therefore poorer design solutions than pairings on the surface plateau. These may still be worthy of selection in the concept design, when considered in conjunction with other criteria beyond the current paired comparison.

Step 3 Surface interpretation. The concept designer would now evaluate to generated adaptive landscape, using their expert opinion of parameter trade-offs and drawing in knowledge of other design criteria, to assess global optimum selection of combined product attributes. The selection surfaces are a guide to trade-offs and sensitivity to variation in design parameters, rather than absolute limits to design values.

Interpretation of the adaptive landscapes and selection of design parameter values is an iterative process that requires the designer to continually review interrelations between design attributes.

The representation of the surface may be further simplified by adopting contour layers to represent each level of fitness applied to that surface.

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