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# Uncertainty modelling for extended product lifecycles: Application of a biological analogy to product lifecycle management

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**Keywords**: Adaptive landscapes; product lifecycles; product geometry.

**Abstract**: Product lifecycles are determined at a point in the planning process where there is great uncertainty in future market conditions and drivers for change. Particularly for products with high investment costs and long lifecycles, the period of production may be considerably longer than the change cycle for new technical developments, legislation changes, market conditions, etc.

Using internal combustion (IC) engines as an exemplar of products with long planned lifecycles (10-20 years) and heavy investments (~£200M), a model has been developed to help predict probable, but uncertain, geometry changes in product architecture over expected lifecycles. The model draws on a biological analogy to apply adaptive landscapes to product architecture choices, building in robustness to requirements variation over the life of the product.

The model has been applied to historical examples of the evolution of a family of products from first introduction, through to end of production. In this way, actual lifecycle extension, modification and change can be compared to modelled approaches to validate heuristic values to be used in future product planning.

The use of adaptive landscapes allows products to be defined in such a way that they are more robust to ill-defined, but reasonably expected changes in product configurations and requirements. Thus, reducing total lifecycle investment costs and allowing products to be more responsive to changed circumstances. Through this process, the lifecycle of products can be extended for minimized cost of change.

## Introduction

*'It is not the strongest of the species that survives, nor the most intelligent; it is the one that is most adaptable to change'*

Charles Darwin

New products are developed to satisfy defined customer needs, working within the constraints of known expectations over the life of the product manufacturing period. Taking the product lifecycle to mean the period over which a product is conceived, developed, launched to market and is in production, the end of life is therefore determined when a product line ceases to be manufactured.

The word *lifecycle* implies a biological analogy to the life history of an individual biological entity – its development over time and the evolution of its form throughout its many changes (Stearns 2004). This approach can be applied to species development, as the general physical arrangement of an entity evolves, driven by dominating environmental conditions (McGhee 2007). The physical configuration of a species is therefore more or less *fit* in relation to the environment in which it exists (Dieckmann *et al* 2011).

Darwinian natural selection is now well established as the driving mechanism for development in nature (Weibel 1998). The essential elements of evolutionary theory being variation, selection and inheritance. The selection process in biology working on the basis of the concept of ‘fitness’.

Fitness can be seen as a dynamic, optimizing process. Flora and fauna that have greater degrees of fitness for attributes that enable survival and reproduction, are more likely to pass on their genetic materials to future generations. In recent decades, this concept has been applied to a number of fields outside biology, such as economics (Dosi & Nelson 1994), social behaviours (Godfrey-Smith 2012), business operation (Piepenbrock 2009) and engineering (Whitacre 2012).

Technological products can be thought of as evolving under the pressure of environmental constraints, in the same manner as biological entities (Brasalla 1988). Techniques to apply evolutionary methods to design and engineering have led to such methods as genetic algorithms, biomimicry and other methodologies that apply a biological analogy to optimization in design (Businaro 1983, Bentley 1998, Schatten & Zugaj 2011).

As the quote from Darwin at the start of this paper suggests, fitness in a biological environment refers most often to a collection of attributes that are *good enough* to ensure survival, rather than optimal in any mathematical sense.

One of the challenges of designing engineered products is to ensure that they are robust to uncertain future conditions. The science of engineering and the discipline of design is dominated by optimization. Products are developed to meet known requirements in as optimal a way as possible, against multiple criteria. Known variations in conditions and requirements are catered for by ensuring robustness to defined degrees of variation, often through the use of modular design or planned capacity in the design for adaption to variation at a later date. The challenge arises when possible future changes to product geometry is expected, but uncertain.

Under these circumstances a price will be paid for building excess capacity for adaption at a future date, in the form of product geometry that is sub-optimal for size, weight or other key product characteristics. The product designer must therefore balance the need to launch a product to market that suits the immediate needs of the marketplace, whilst having capacity for extended life built in to minimize the costs of change at a later date.

## Methods

Modeling and simulation

### *Adaptive Landscapes*

The concept of adaptive landscapes (AL) was first proposed by Sewall Wright in two short papers in 1931 and 1932 and later expanded in a more complete coverage in later years (Wright 1969 & Wright 1988). Wright proposed a ‘landscape’ where the ‘terrain’ of that landscape is generated by the fitness function resulting from the interaction of the functions of two biological attributes. The adaptive landscape theory has a long history adoption and although less than perfect as an analogy, it nonetheless has proven useful in modelling evolutionary pressures on driving speciation and change (Ruse 1990).

Higher peaks on the landscape would indicate higher fitness – a desirable position to achieve to ensure survival. Valleys and low lands on the landscape would indicate sub-optimal combinations of features and attributes, best avoided to ensure a longer life.

The flora or fauna under consideration would have a number of combinations of attribute, each with a corresponding landscape. The value of defining these landscapes are three fold:

1. **Visualization** – Landscapes allow a clearer visualization location and of range of fitness peaks

2. **Optimization** – Relative fitness peak heights define optimal solution locations, enabling ‘peak jumping’ for global solutions rather than local optima

3. **Sensitivity** – The slope of the fitness landscape at any point indicates the sensitivity to change when moving away from a current location

As attributes change, they move across the landscape surface finding a place higher or lower on the fitness surface. Darwinian evolution tells us that those attributes that find themselves at higher elevations are more likely to survive.

### *Product Adaptive Landscapes*

Applying adaptive landscapes to product designs, key attributes can be modelled to better understand the interaction of features and find optimal configurations.

When applied to product design, adaptive landscapes have been used successfully to uncover optimal peak points.

Within a design space, locations on the landscape may fail to meet essential levels of performance. Searching the landscape in these regions is unproductive and is to be avoided. By ‘flooding’ the landscape to a depth equivalent to the contour level associated with infeasible attribute combinations, a clear cut-off to the design search space is established. Any attribute combination above the flooded plane is therefore feasible and an acceptable solution. The remaining landscape above the flooded plane can then be searched for optimal peaks. This landscape can be referred to as a flooded adaptive landscape (FAL).

Product attributes defined by the adaptive landscape can be thought of as key physical geometry that determines functional characteristics of the product and therefore its ability to ‘survive’ in the marketplace. Considering Darwin’s definition of fitness being related to adaptability to change, a relatively flat optimal peak would allow adjustments in attribute values i.e. changes in geometry, with little change in optimization.

Considering the optimal peaks as an adequate ‘truncated plateau’ to the landscape, allows the designer to put adaptability into the right context for making product configurations robust to change. This modified peak adaptive landscape can be referred to as a truncated adaptive landscape (TAL). Combining both flooding and truncation generates a truncated, flooded adaptive landscape (TFAL), that defines a zone of robust adaption (the truncated plateau, a zone of feasible, but sub-optimal solutions (the landscape slopes) and a zone of infeasible or otherwise undesirable solutions (the flooded plane).

Figure 1 shows a product design adaptive for representative attributes ‘A’ ($At_y$) and attribute ‘B’ ($At_x$). The fitness function ($Ft_z$) is defined by the landscape peaks.

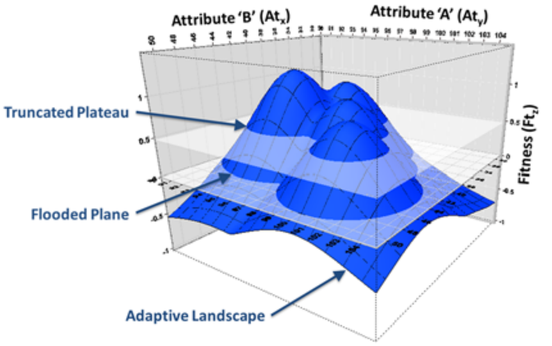


**Figure 1. Product Adaptive Landscape.**

The truncated, flooded adaptive landscape therefore generates a ‘slice’ of landscape that is feasible for exploration.

### *Internal Combustion Engine Feature Modelling*

Internal combustion (IC) engines are capital intensive products, with a long product production lifecycle. Over the production life of an engine, many changes in geometry may be necessary to cope with changing requirements to meet new standards, customer feature and performance expectations and to respond to market drivers, such as new competition.

Investigations into the investments required into engine production facilities and tooling show costs in the £80-250m range for automotive applications. The tooling and equipment for large scale engine production is usually dedicated to the production of fixed product geometry. Building in flexibility adds considerable cost (15-30% additional cost) which manufacturers are reluctant spend if there is not a good rationale justifying the expenditure. This flexibility is to adapt the product to often ill-defined changes 5-10 years after production has started, 8-12 years after the geometry for the product may first have been defined during the concept design stage of the products life.

Truncated, flooded adaptive landscapes allow the designer to understand the sensitivity to geometry change, whilst considering feasible solutions. By defining TFAL landscapes for key geometric attributes of engine designs, degrees of uncertain, but reasonably expected geometry change can be considered.

As the exact geometry changes that may be required at some distant point in time are unknown, a probabilistic approach to assessing the requirements is used.

Figure 2 shows the design process developed. Heuristics derived from similar prior engine life histories are generated. These are used to moderate the requirements for the new product, generating a set of inputs into a multi-criteria decision making process. The outcome of this initial optimization stage is to define an adaptive landscape - a design space within which further optimization can occur.

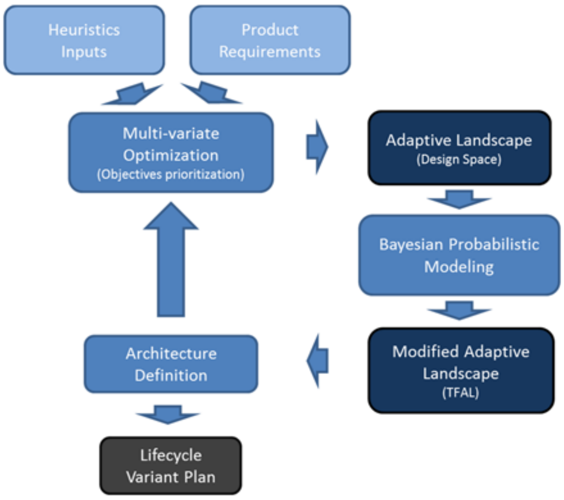


**Figure 2. Adaptive Landscape Design Process.**

Applying a probabilistic approach to expected changes and its sensitivity to adaption, a modified truncated, flooded adaptive landscape is produced (TFAL).

The TFAL solution space is used to select appropriately robust geometry to move forward into embodiment design.

The robustness of the TFAL model defines what variants in product geometry are possible without additional capital equipment and tooling changes (on the truncated plateau) and which are feasible, but may require further investment (on the landscape slopes). It also clearly defines infeasible solution sets (the flooded plane) that would require a new engine program or major reinvestments to satisfy.

## *Application of the TFAL Model*

The application of the TFAL model can be seen in Figure 3. Here an adaptive landscape has been generated based on benchmarking data of existing engine designs and provisional analysis of feasible zones based on known geometry limitations and manufacturing constraints. Input data from competitor benchmarking, current product offerings and concept analysis is usually sparse. A 3D surface for the adaptive landscape is generated from a point set which may only consist of 5-8 data points. The validity of this surface is checked against known feasible solutions using datasets with 200-300 data points from benchmark data.

A Bayesian probabilistic model, utilizing historical heuristic data on likely geometry changes over the expected production lifecycle is used to generate a flooded plane and truncated peak.

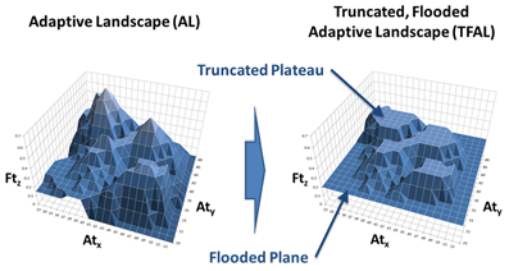


**Figure 3. TFAL Landscape Generation.**

The resulting TFAL landscape is used to explore geometry selection options, with an emphasis on a design configuration that will be robust under conditions of uncertainty, rather than finding a theoretically optimal design against current conditions.

## *Pareto Frontiers*

The landscape truncated peaks generated may be a single surface, or several dispersed surfaces that represent optional equally optimal peaks.

Attributes may interact in such a fashion that a Pareto frontier defines an optimal edge to the design space. Figure 4 shows a 3D adaptive landscape of the Pareto frontier edge. Outside of the frontier, fitness values drop off markedly to an infeasible zone. Behind the Pareto frontier lies a feasible plane, with gradually diminishing optimality as solution sets move away from the frontier.

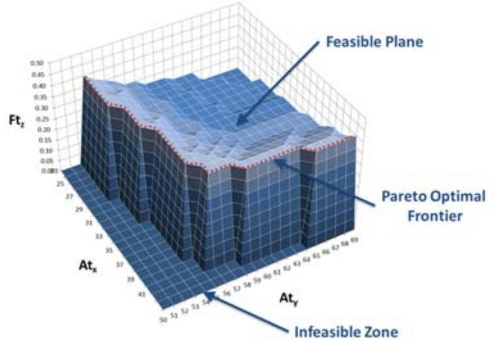


**Figure 4. 3D Pareto Frontier.**

Figure 5 shows a 2D representation of the Pareto frontier where all solutions along the frontier are considered equally good.

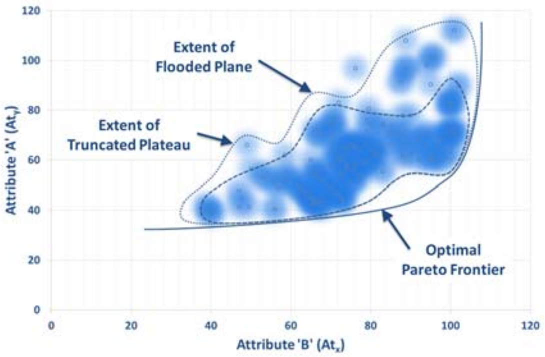


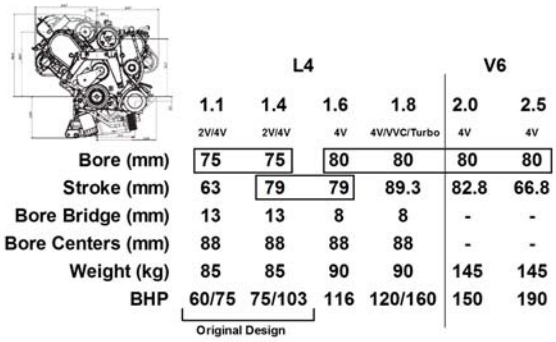
**Figure 4. 2D Pareto Frontier.**

Superimposed on the map of the frontier are the extent of the truncated plateau and the flooded plane. Using a 2D representation of the TFAL surface is more useful in enabling the designer to move from a visualization tool into using the TFAL surface to select appropriate values for consideration in the design configuration.

## Conclusions

Product lifecycle changes can have profound effects on the economics of a business (Spitzley, Kim & Keoleian 2005). The TFAL design approach was applied to some historical engine life histories to validate the approach and estimate the potential impacts it could have on financial and environmental performance.

Several engines with well documented development histories were chosen to retrospectively apply the TFAL process. One example is the Rover K Series engine which was originally developed as an inline four cylinder engine of 1.1l and 1.4l displacement. Due to unexpected changing requirements over the production life of the engine, it was eventually produced in six displacements across inline and vee configurations, as a 4 & 6 cylinder engine. Further developments included turbo-charged and Diesel variants (Hammill 2010).



| | L4 | | | | V6 | |
|---|---|---|---|---|---|---|
| | 1.1<br>2V/4V | 1.4<br>2V/4V | 1.6<br>4V | 1.8<br>4V/VVC/Turbo | 2.0<br>4V | 2.5<br>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 | | | | | |

**Table 1. Rover K Series Engine Geometry.**

The original design of the Rover engine was optimized for low weight and compact size, driven by a need for fuel economy and efficiency. The geometry changes of bore/stroke and configuration meant that many of the primary enablers of the early design features, such as through bolting and low-pressure die castings, needed significant additional reinvestment to continue to be used.

A consideration of past developments of similar engines and scenario planning for probable but uncertain future features demands through adaption of TFAL would have avoided nearly 70% of the subsequent additional investment to extend the production life of the engine family.

Similar validation activities were done using engine production life histories of the Chrysler 2.5l four cylinder engine (Weertman 2007), the BMW GS Boxer engine (Schneider & Koenigsbeck 2009), BMW K Series (Walker & Dobson 1989) and the Coventry Climax racing engine (Hammill 2004, Robson 1975).

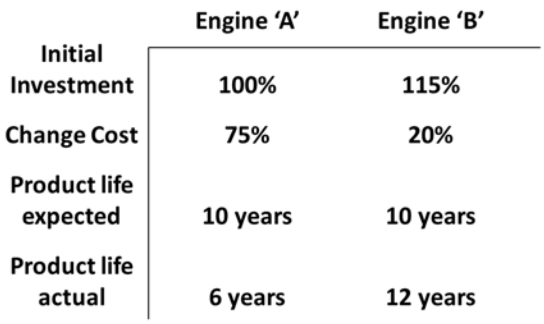
These engines were chosen as they have long production lifecycles, have undergone significant architectural configuration development post production launch and have been produced in high volume, therefore meeting the criteria for application of the TFAL methodology.

Adaptive landscapes were developed from an analysis of sensitivity to change in key geometry architecture, such as bore/stroke ratio, cylinder block height and camshaft centres. Truncated, flooded adaptive landscapes were derived to bound the limits of adaptability within the constraints of manufacturing equipment fixed geometry. Heuristics were drawn from these historical examples that can be applied to future engine configuration work.

Production end of life for engines is most usually arrived at when geometry changes required due to the needs of engine evolution obsolete existing manufacturing equipment.

Table 2 indicates the cost of building adaption capability into a product design, using the TFAL method. Initial costs are 15% higher and the product may be marginally sub-optimal compared to competitive products on the market for size, weight, etc.

Building in robustness to IC engine geometry using the TFAL modelling method, will extend the life of the engine in production. It is estimated that on a typical engine project, 3-8 year of extra production life could be added by building in adaptive capacity. The average automotive engine production life before major change is 5.5 years. Application of TFAL therefore has the potential to extend production life by 50-140%.



| | Engine ‘A’ | Engine ‘B’ |
|---|---|---|
| Initial Investment | 100% | 115% |
| Change Cost | 75% | 20% |
| Product life expected | 10 years | 10 years |
| Product life actual | 6 years | 12 years |

**Table2. Adaption Costs**

The main driver for geometry change in IC engines is a need to comply with emissions regulation introduction. Emissions legislation is typically applied on 3-5 year cycles, which means that a new engine design will need capacity to cope with an expected 2-4 major changes in emissions requirements over its production life. Changes to legislation and market conditions are thus expected, but not fully defined or known at the point of concept design.

Building robustness into the design allows for these changes to be adopted with minimal re-investment. Extending the production life of the engine in production reduces waste through greater utilization of investments already made. The cost of change is minimized by building in robustness to change, therefore using resources more efficiently.

A more robust approach to product geometry definition therefore brings environmental benefits in terms of better use of resources as well as faster adoption of product to meet new environmental standards.

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