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Attribute and Technology Value Mapping for Conceptual Product Design Phase

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Abstract

The main focus of this paper is how the concept design phase of the product development process can be improved by using an objective data-driven approach in selecting a final concept design to progress further. A quantitative new test-bed 'Product Optimisation Value Engineering' (PROVEN) is presented to critically assess new and evolving powertrain technologies at the concept design phase. The new test-bed has the ability to define a technology value map to assess multiple technical options as a function of its attributes, whose precise values can be determined at a given cost. A mathematical model that incorporates a highly adaptable, data-driven and multi-attribute value approach to product specification and conceptual design is developed, novel to the concept design process. This creates a substantially optimised product offering to the market, reducing overall development costs while achieving customer satisfaction.

Keywords

Conceptual Design, design research, design optimisation, project management, design.

1. Introduction

The early phase of product development is referred to as the concept development phase which ends with a final concept decision. This crucial decision must allow for further detailed design development to be carried out resulting in a finished product as described by Ullman.[1] The limited knowledge and incomplete key information available at this phase creates uncertainty

which coupled with the abstract nature of the design concepts makes the decision making process very challenging.

'Many Research and Development (R&D) technology selection techniques have been developed in the last 30-40 years, but few have been used by R&D companies in industry. In fact, the methods used aren't much more advanced than two or three decades ago, even though the state of the art has advanced rapidly.' As quoted by Szakony[2], there are very few techniques applied at the early concept design phase to determine the correct technology selection and these techniques have not advanced all that much during the last twenty to thirty years. The need for research on the concept design selection process within product development, and engineering design has been recognised in previous research by Ulrich & Eppinger.[3] This highlights the need for further research to improve the initial concept design selection process. As product development companies have to compete on a larger global level than before, the ability to select the correct technology configuration during the early concept design phase provides a greater advantage.

In summary, it is critical during the Product concept design phase to achieve the right balance between function vs. cost to deliver the necessary 'value add' to the end product configuration as perceived and valued by the customer. This paper presents how the concept design phase of New Product Development (NPD) can be improved using a data-driven objective approach in the selection of a final product concept design to progress further. A quantitative new test-bed 'Product Optimisation Value Engineering' (PROVEN) is proposed to critically assess new and evolving automotive powertrain technologies at the concept design phase, unique to the product development process. This will enable the concept design team to make critical decisions in the selection of various concept designs with more extensive knowledge of the impact the technology will have on the final product design.

2. Theoretical background

In the early conceptual design phase, cost modification is relatively low and the opportunities for realising a cost effective solution are high, compared to the later phases of the design process where late engineering changes drive high costs as stated by Ferguson.[4]
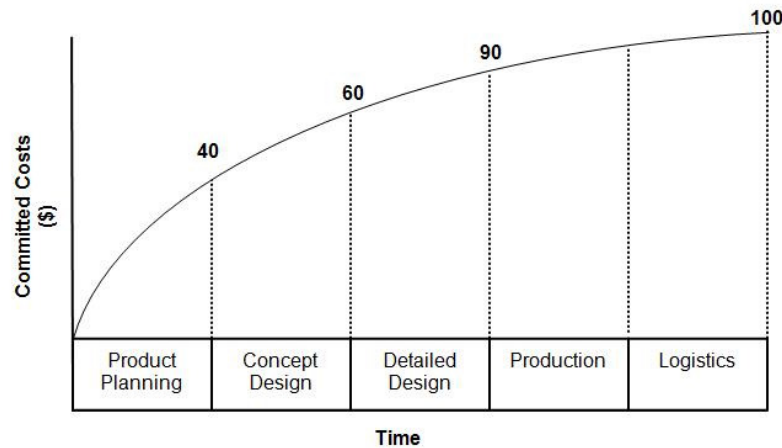

Figure 1: Committed Product Development costs[4]

Figure 1 displays the typical costs encountered during the various phases of the product development process. Once a product is designed, as much as 90%-95% of a products cost are committed with late design changes normally driving a redesign of the product. The early front-end phase of product development is one of the most critical and influential aspects in defining the specification and conceptual design of new products. This phase of development requires the interaction of many interdisciplinary groups using a systems engineering approach.

2.1   Concept Design Process

The selection of a final concept design can be challenging as this involves input from many areas of the business including marketing, business strategy office, manufacturing, finance and engineering described by Khurana & Rosenthal.[5] Choosing the correct concept design to

ultimately create a product that customers value and will want to buy while taking into account all of the internal business factors is vital. This requires a carefully managed team using appropriate tools and methods to assist in arriving at a final concept design objectively.

Subjective decisions used during the concept design evaluation stage can lead to the wrong design being selected resulting in many costly design iterations further down the product development process and can result in undesirable products being produced. Subjective decisions can occur, as design engineers can become emotionally attached to a particular design pushing for their design to be accepted even though it may not deliver the key performance attributes. This can heavily influence the final concept design selected while potentially discounting better concept designs in the process.

Within the literature relating to concept design selection methods, the use of a decision matrix for the evaluation of concept design alternatives performed within a team are suggested to assist the design selection process. When criteria are identified, caution must be used as the use of too rigid and formal assessments may create barriers in the early phases of product development that can inhibit innovative ideas coming through stated by Hammedi et al.[6] Subsequently, concept decision making is continually occurring as a phenomenon during the concept development process that are characterised by uncertainty and vagueness, although the decision making approach and methods used are rarely transformed or radicalised described by Malak et al.[7]

2.2 Value Engineering

This section describes various 'value' mathematical and analytical approaches for achieving a purely objective basis in assessing various product concept design proposals. Within the context of Product design, value is defined as achieving all intended functions at the lowest cost

that is one of the key aims of this research. The principle of value engineering is based upon equation (1):

Value = Function
       Cost   (1)

By increasing the functional capability of a product and maintaining cost, the overall product value is increased. Alternatively, by reducing the cost and maintaining a required level of product functionality, value is also increased. As stated by Kaufman[8], making trade-off decisions relative to cost using this value equation is valid at a component level but is not effective at a system level where trade-offs between two attributes that have different measures of performance requiring a comparison to be made between quantities having different units.

The use of Value Curves (VC) provides a method by which the attribute value assessment is based upon the premise that the value of performance attributes can be represented by continuous value curves if the performance measure is itself continuous stated by Donndelinger et al.[9] Taguchi[10] states that a Quality Loss Function offers a method to assess the value of a product or service to the customer, allowing for a valued based decision process to be taken. A loss of quality only occurs when a product falls outside the specification limits (+/-), typically quantified in terms of the repair cost 'A' shown in Figure 2.
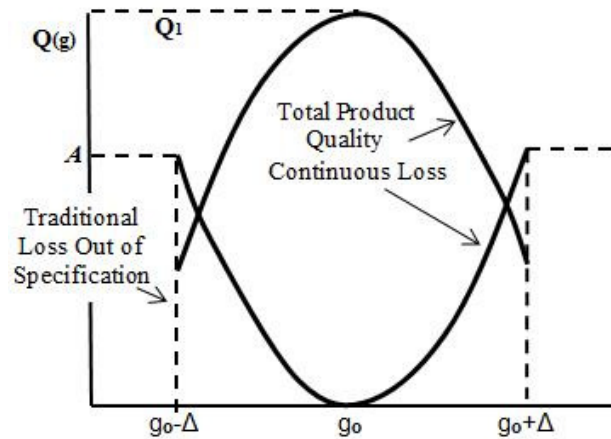
Figure 2: Traditional and Taguchi Losses[10]

Taguchi emphasises the importance of producing products that are as close to the nominal g_o specification line as possible and any change from the g_o line is considered a deviation.

Traditional manufacturing practices strive to produce products within a specification $\pm \Delta$ of a nominal attribute level g_o. A loss of quality is assumed only when products fall outside the specification and is typically quantified in terms of the repair cost A (Figure 2). As long as the attribute g is within the $g_o \pm \Delta$, then the quality level is treated as if it were g_o and no losses are assumed. Instead, the importance of producing products as close to the nominal specification as possible is emphasised in the loss function by representing a continual loss of quality as a result of any deviation from g_o. The total quality of the part or product Q (g) is then based on the level of attribute 'g' as shown in Figure 2.

The relationship of value curves versus vehicle attributes expressed by exponent gamma (**γ**), weights the attribute and can be used to analyse the trade-offs between the various powertrain technologies. For example, the value change due to an increase in horsepower (an attribute of the engine subsystem) should be determined through the sum of the changes in value it generates in system level attributes such as acceleration, top speed and fuel economy.

2.3 Cook's Extension to Value

In estimating the value of products, Cook[11] extends Taguchi's quality loss function to a value loss function. The term 'value' is important to clarify in the context of an economic trade-off for consumers extending beyond conventional manufacturing 'quality' or technical 'performance'. In addition to normal attribute level g_0, Cook introduces the concept of an ideal attribute level denoted as 'g_I', at which further improvement in the attribute is of no additional value to the stakeholder and the critical attribute level 'g_C' at which further degradation in the attribute renders the product as a whole worthless. Variations in vehicle values expressed as $v(g)$, are attributable to changes in product performance measures and expressed as ratios relative to the value of a baseline vehicle.

The relative value of a product as a result of a single attribute at level **g** located between g_C (critical) and g_I (ideal) is then given by Cook's value equation (2):

$$v(g) = \frac{V(g)}{V_0} = \left[\frac{(g_C - g_I)^2 - (g - g_I)^2}{(g_C - g_I)^2 - (g_0 - g_I)^2}\right] \tag{2}$$

where:

- $v(g)$ is the customer perceived value of a vehicle with performance g
- V_0 is the customer-perceived value of the baseline vehicle
- g_I and g_C are the ideal and critical value of the S-model curve for a performance measure
- g_0 is the performance of the baseline vehicle

An adaptation of Cook's value equation with the introduction of γ to represent an assigned weighting factor for the importance each performance attribute carries, has been made as shown in equation (3).

$$v(g) = \frac{V(g)}{V_0} = \left[\frac{(g_C - g_I)^2 - (g - g_I)^2}{(g_C - g_I)^2 - (g_0 - g_I)^2}\right] [\gamma] \tag{3}$$

As attributes tend to have different units of measure, Cook's equation normalises all values to 1.0 allowing for an easier comparison to be made particularly with a rather complex system to be evaluated. The ideal point 'g_I' of the value curve is defined as the performance level at which the derivative of the value curve reaches zero. This means that any further improvement in this performance measure does not improve the customer-perceived value of the vehicle. The critical point 'g_C' is defined as the performance level at which the value curve crosses the performance axis, meaning that at this point or beyond the performance of the product is so poor that the customer perceives the vehicle to have absolutely no value.[11] The ideal and critical points are established for each performance measure through key dialogue with the product engineering team. The weighting factor, however, may vary between the market segments to account for differences in customer preferences. Weighting factors are determined for each attribute for the importance they serve contributing to the total value of the product as perceived by the consumer.

2.3 (a)   Relative Value Index Model (RVI)

The Relative Value Index (RVI) is a mathematical model based on the Taguchi's loss function, adapted from statistical process control methods. The RVI is more meaningful as actual data is derived from each of the attribute performance parameters to generate a value index that can be used to compare between various attributes where units of measure maybe different, stated by Downen.[12]

The total value of a product taking into account as many attributes as required can be calculated using a Relative Value Index (RVI) based on Taguchi's loss function[12] shown in equation (4):

$$RVI_i = v(g_{i_1})^{\gamma_1} \, v(g_{i2})^{\gamma_2} \, v(g_{i3})^{\gamma_3} \, \dots v(g_{in})^{\gamma_n} \tag{4}$$

An adapted version of the RVI equation has been developed to calculate the average relative performance values for a concept design, as follows, where 'n' represents the number of attributes assessed in equation (5):

$$RVI_i = \frac{v(g_{i1})\,\gamma_1 + v(g_{i2})\,\gamma_2 + v(g_{i3})\,\gamma_3 \ldots v(g_{in})\gamma_n}{n} \tag{5}$$

The exponential weighting factor 'γ_n' reflects the relative importance of each attribute to the overall product RVI of the attributes g_i. This equation is derived from the Cobb-Douglas utility function of economic theory and in this form the system is rendered worthless if any single attribute reaches a critical point g_c. The multiplicative relationship between the attributes means that a specific product attribute depends not only upon its own level but also on the levels of the other attributes.[12] When assessing competing concept designs for their suitability against a set of performance attributes, the use of the RVI metric allows for easier comparisons to be made providing a metric value between 0-1.

2.3 (b) New Technology Cost Calculation

To help determine a viable business case for the implementation of a new technology it is important to understand the relative worth in monetary terms a new technology contributes to delivering customer and legislative performance attributes of a product.

A prioritisation of performance attributes can be used as a first step to estimate the relative value each technology is worth to a company by establishing how much the company is prepared to pay for meeting each new performance attribute target. For example, fuel economy efficiency improvement is one of the most important attributes car manufactures are continually investing in with the application of advanced and evolving technologies. Given a scenario where a new vehicle design requires a 10% fuel economy improvement, a business equation can be

defined to determine how much the business is prepared to pay for new technology to make economic sense.

This can be achieved by taking into account the following factors to estimate a cost the company is willing to pay to deliver attribute improvements for a new product:

1) Projected sales volume of new vehicles to be sold determining economies of scale;

2) Customer willingness to pay for improved attributes linked to overall cost of vehicle ownership and initial purchase price of vehicle;

3) Calculated increased value to overall brand strength for future products.

If for example a car manufacturer has estimated that it is economically viable to spend 16$ to develop new technology for every kilogram of weight saved, this serves as a useful guide to assist the concept design technology selection process.

The following three defined steps can be used to identify a net cost benefit new technologies can offer a company when assessing concept design alternatives.

Step 1: Determine Attribute value to company in ($)

Taking into consideration the three cost factors as stated, Table 1 displays the cost an automotive company may invest for improving each performance attribute to deliver a new vehicle programme.

Table 1: Company Attribute Value $

Performance Attributes	$ Value
Performance (bhp)	20 $ per PS
Weight (kg)	16 $ per kg
Filtration Efficiency (%)	14 $ per %
NVH (dB)	20 $ per dB
Package (Volume)	10 $ per mm

Step 2: Total Attribute Value ($) for each concept design

Equation (6) calculates the attribute value to the company for each concept design to be assessed, given as:

(Achieved performance value * $ value) = Attribute value to company $ (6)

The attribute cost assessment of a concept design is calculated by multiplying the achieved performance values related to a concept design by the dollar value the company is willing to pay.

Step 3: Net Value ($) of each concept design

The net value cost related to each concept design is a measure of how cost effective each design is to the company in delivering the key performance attributes. Equation (7) calculates the net value of each concept design to the company can be expressed as:

(Total Attribute Value to the company - Total System Cost) = Net Value $ (7)

The net value expressed in dollars for each concept design alternative represents the potential net value each concept design offers to the company.

3 PROVEN Test-bed

As described in Section 2, it is critical for the correct concept design to be selected influencing the entire product development process minimising late design changes that typically attracts high cost and risk in launching a new product to market on time. Therefore the application of the PROVEN test-bed at the concept design phase will achieve a right-first-time approach, eliminating late design changes using a systems engineering approach. The theoretical background review revealed the application of an adapted version of Cook's value equation

provided a means to objectively assess various concept designs against a number of performance attributes.

Figure 3 provides a summary of three key steps formulating the PROVEN test-bed. This provides an objective data-driven approach in achieving a highly optimised 'value' powertrain concept design. The foundation of the PROVEN test-bed uses the basic principle of the value equation where function is divided by cost and a maximum product value is realised by increasing product functionality while minimising cost.
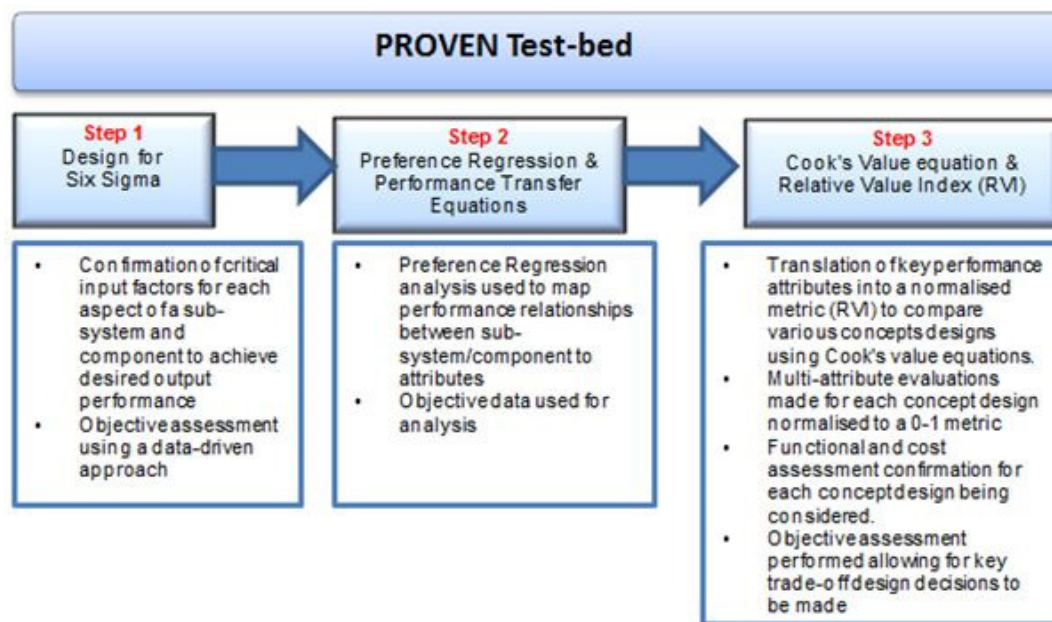

Figure 3: PROVEN Test-bed Applied to Concept Design Phase

Step 1: Design for Six Sigma

The first step of the PROVEN test-bed is utilising the Design for Six Sigma methodology. The Design for Six Sigma methodology offers a useful data-driven approach in identifying the critical sub-system(s) and component(s) having a significant impact upon achieving required attribute

performance targets. The design for six sigma approach serves as an appropriate first step in confirming the critical key input factors (and inter-related subs-systems in terms of performance) for each aspect of a sub-system/component to achieve the required performance expressed as an output. The function of each powertrain sub-system and component can be expressed in mathematical terms to show how they influence the target 'y' attribute.

This can simply be expressed in mathematical terms described by Downen et.al[12], Equation (8):

y = f(x) $\hspace{8cm}$ (8)

where:

y = output target performance measure

x = critical performance characteristic

f = function of critical characteristic 'x'.

Equation 8 provides the foundation for identifying and mapping out the relationships between key powertrain sub-systems and components serving as the 'x' inputs and their influence upon the target performance attributes denoted as the 'y' outputs.

Step 2: Preference Regression

The second step of the PROVEN test-bed is the use of Preference Regression analysis as described by McCarty et.al[13], Equation (9):

y = ax + b $\hspace{8cm}$ (9)

where;

x = critical performance characteristic(s)

a = slope of the linear curve

b = intercept of the curve on y axis

Preference regression is used to map performance inter-relationships between sub-systems and components and provides a means to achieve the optimal performance settings through trade-off analysis. For example to rate a new air induction system design for an automobile, key critical performance characteristics denoted as 'critical 'x's' are calculated such as effective back pressure and noise attenuation which are then translated into Power (bhp) and Noise Vibration Harshness (dB) performance attribute effects, denoted as the 'output 'y's'. For instance, if NVH is rated as a high impact attribute taking priority over all attributes to achieve the required end-product value and the design of a new air induction system achieves impressive NVH performance, this design would be preferred. However, an air induction system that only delivers outstanding NVH is not very useful if it does not meet the required engine performance level. Hence, it is important to note that although in this example NVH was deemed a priority, other attributes must also be considered during the concept design phase to ensure other critical system performance aspects are also achieved.

Using Equation 9, a regression analysis has been performed to map the influence of the air box volume (represented as the critical input 'x') upon NVH performance shown in Figure 4.
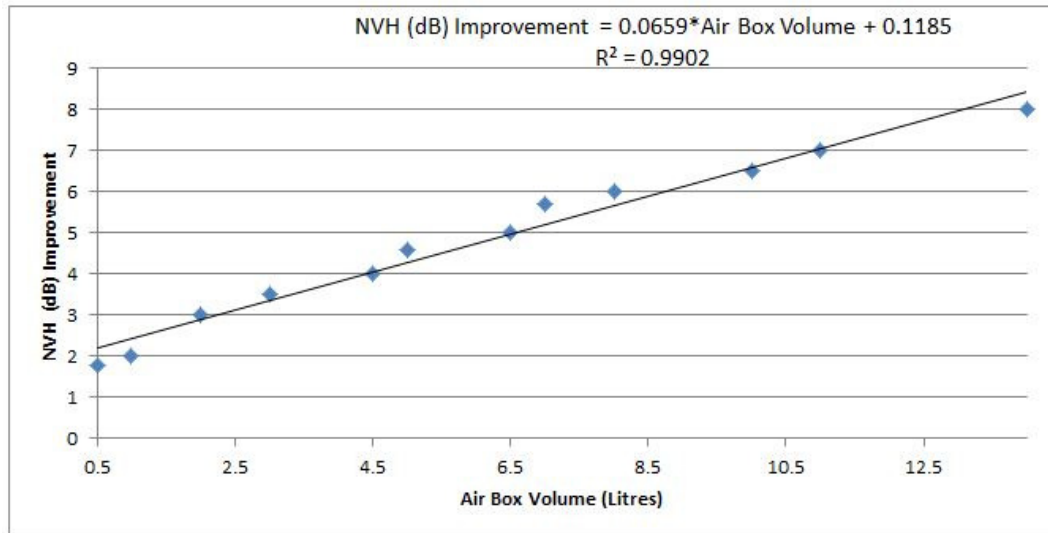
Figure 4: Regression analysis of Air box volume and NVH

From Equation 9 this gives the following linear regression Equation (10):

NVH (dB) Improvement = 0.0659 * Air Box Volume + 0.1185   (10)

The regression analysis confirms there is a linear relationship between the volume of the air box and the improvement realised for the NVH attribute. A larger air box volume improves the NVH characteristic but this must be balanced with other attribute factors such as peak power engine performance in order to identify an optimum air box design. The output of the regression analysis can be matched with the weighting factors assigned to each key performance attribute confirming the net functional value of a concept design in meeting the target attributes.

There are instances where performance relationships between one sub-system and another may be non-linear. To evaluate and analyse these relationships non-linear methods can be used that include logarithmic functions, trigonometric functions and exponential among other fitting methods. The end result confirms the performance relationship between a set of independent variables and a dependant variable.

Further analysis including both linear and non-linear regression can be performed for all other critical 'x' inputs to determine the required performance for each powertrain sub-system to achieve the required target attributes for a new vehicle programme. A technology value map can therefore be created to support the concept design phase.

Step 3: Cook's Value equation and Multi Attribute Utility Theory (MAUT)

The third step of the PROVEN test-bed is to confirm the value of a technology expressed in terms of function and cost rated against performance attributes. Cook's value equation provides an objective driven approach in assessing concept designs to a normalised metric 0-1 (RVI) against a set of pre-defined performance attribute values. As the end result of the RVI calculation uses a normalised value of (0-1), this allows for a number of different attributes to be assessed particularly useful when dealing with a complex system. Leading on from this, a multi-attribute equation provides a combined value rating of all attributes assessed for each concept design into one single decimal rating. This also reduces the risk of subjective assessments made. A new technology cost equation offers the possibility to estimate a relative cost related to a concept design aiding the final design selection process. As Cook's value equation and the multi-attribute approach are essentially the centre piece of this research in evaluating concept designs, it is important to test the theory by means of a case study[14].

4 Case Study: Powertrain Air Induction System

To test Cook's equation and to identify its usefulness and limitations, the following worked example using the Air Induction System (AIS) sub-system of the Powertrain is used. There are different types of AIS's available to assist in the power deliver required for an internal combustion engine each having their own benefits and trade-off's mainly on power

performance, weight, NVH and package. These attributes will be chosen for this example to assess three different air induction designs.
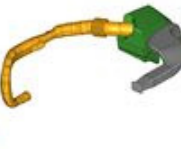
Following Cook's procedure, the first step is to set the target values for the key performance attribute bounds that include; baseline (g_0), critical (g_c) and ideal (g_I) as shown in Table 2. These performance attribute bound values have been determined based upon empirical historical data and are aligned to the performance requirements of a new vehicle programme. The weighted importance factors denoted by (γ) for each attribute criteria have also been defined based upon internal company data and represent a prioritisation of attributes developed specifically for the turbo unit of the Powertrain system. It is recognised that the weighting criteria plays an important role during the concept design selection process and deriving an accurate value based on actual known performance is key. The weighting values assigned for each key attribute have been determined using historic marketing data confirming the priority and importance of each attribute as valued by the customer.

Table 2: Performance Attribute Bounds

Attribute (g)	Attribute Bounds			Weighted (γ)
	Critical_c	Target_0	Ideal_i	
Performance (bhp)	2	4	6	1
Weight (Kg)	5	7	12	0.8
Filtration Efficiency (%)	6	5	3	0.7
NVH (dB)	0.6	0.4	0.2	1
Package (Volume)	2	5	7	0.5

With attribute bounds defined as shown in Table 2, a performance assessment for each air induction design has been made against each of the attribute performance criteria. Substituting these performance values using Cook's Equation 2, provides the calculated Relative Value Index (RVI) for each performance attribute, shown in Table 3.

Table 3: AIS Performance Rating

Performance Attributes	Performance Attribute Targets	Weighting	Concept Design 1 Air Box: 9.5L/Dirty Side Duct: 750mm		Concept Design 2 Air Box: 9L/Dirty Side Duct: 600mm		Concept Design 3 Air Box: 8.6L/Dirty Side Duct: 650mm	
			Achieved Attribute Performance	RVI	Achieved Attribute Performance	RVI	Achieved Attribute Performance	RVI
Performance (bhp)	4	1	3.8	0.93	2.5	0.31	2	0.00
Weight (Kg)	7	0.8	7	1.00	6.5	0.82	6	0.70
Filtration Efficiency (%)	5	0.7	5.1	0.94	4.9	1.05	5	0.81
NVH (dB)	0.4	1	0.41	0.97	0.45	0.81	1	0.31
Package (Volume)	5	0.5	5	1.00	4.7	0.97	4	0.80
Total Relative Value Index (RVI)			0.97		0.79		0.52	
Ranking			1		2		3	

To demonstrate how Cook's equation works, the following defined steps have been laid out assessing Concept Design 1 as an example against the performance attribute;

Step 1; Cook's equation:

$$v(g) = \left[\frac{(g_c - g_I)^2 - (g - g_I)^2}{(g_c - g_I)^2 - (g_0 - g_I)^2} \right] [\gamma]$$

Step 2: Substitute Performance attribute bounds $g_c = 2$, $g_I = 6$ from Table 4 and using the performance value for Concept Design 1, $g = 3.8$ (bhp) from Table 4(a), gives;

$$v(g) = \left[\frac{(2-6)^2 - (3.8-6)^2}{(2-6)^2 - (4-6)^2} \right] [1]$$

= 0.93 (RVI)

The achieved value of 0.93 (RVI) corresponds with the figures stated in Table 4(a) representing the performance (bhp) attribute for concept design 1.

As Cook's RVI equation normalises all calculated values to 1.0, in the case of the performance attribute for concept design 1, it is therefore 93% efficient in meeting the performance target.

It must be stated that as this stage of the analysis when assessing individual attributes for a component, in reality a balance must be achieved for all key attributes to be met. The weighting criteria $'\boldsymbol{\gamma}'$ is derived from the high-level target setting process of a new vehicle programme whereby these target attributes are translated into specific engineering values for each sub-system and component.

The results indicated in Table 4(a), shows concept design 1 scored the highest total RVI for all assessed attributes with a score of **0.97**. This means that 97% of the overall required performance attributes were met making this design the clear winner. Concept design 2 scored 0.79 and concept design 3 scored the lowest RVI of **0.52** and was not effective in meeting the required target performance attributes.

<u>Sensitivity Analysis of Cook's attribute equation</u>

To further test the effectiveness of Cook's attribute equation a sensitivity analysis has been performed for concept design 2 as the achieved score of 0.79 (RVI) shown in Table 4(a) is very close to the winning score of 0.97 (RVI) for concept design 1. This is performed by theoretically equalising the achieved scores for concept designs 1 and 2 for the two highest weighted attributes which in this case were the performance (bhp) and NVH (dB) attributes. For concept design 2 the performance (bhp) attribute is modified from 2.5 to 3.8 and the NVH(dB) attribute is also modified from 0.45 to 0.41.

Using Cooks equation from step 1 and substituting 3.8 (bhp) for the performance attribute gives;

$$v(g) = \left[\frac{(2-6)^2 - (3.8-6)^2}{(2-6)^2 - (4-6)^2} \right] [1]$$

   = 0.93 (RVI)

The NVH (db) attribute is also re-calculated by using 0.41 (dB) within Cooks equation;

$$v(g) = \left[\frac{(0.6 - 0.2)^2 - (0.41 - 0.2)^2}{(0.6 - 0.2)^2 - (0.4 - 0.2)^2} \right] [1]$$
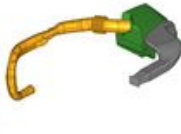
= 0.97 (RVI)

To determine the overall effect on the final score for concept design 2, a multi-attribute assessment is performed by substituting in the figures from Table 4 into Equation 5, gives;

$$\frac{(0.93 + 0.82 + 1.05 + 0.97 + 0.97)}{5} = 0.95 \text{ (Total RVI)}$$

Table 4 displays the results for concept design 2 that can be compared to concept design 1.

Table 4: AIS Sensitivity Analysis

Performance Attributes	Performance Attribute Targets	Weighting	Concept Design 1 Air Box: 9.5L/ Dirty Side Duct: 750mm		Concept Design 2 Air Box: 9L/ Dirty Side Duct: 600mm		Concept Design 3 Air Box: 8.6L/ Dirty Side Duct: 650mm	
			Achieved Attribute Performance	RVI	Achieved Attribute Performance	RVI	Achieved Attribute Performance	RVI
Performance (bhp)	4	1	3.8	0.93	3.8	0.93	2	0.00
Weight (Kg)	7	0.8	7	1.00	6.5	0.82	6	0.70
Filtration Efficiency (%)	5	0.7	5.1	0.94	4.9	1.05	5	0.81
NVH (dB)	0.4	1	0.41	0.97	0.41	0.97	1	0.31
Package (Volume)	5	0.5	5	1.00	4.7	0.97	4	0.80
Total Relative Value Index (RVI)				0.97		0.95		0.52
Ranking				1		2		3

Although the values have been altered for concept design 2 achieving a total RVI of 0.95, concept design 1 leads with an RVI of 0.97. This means that all other attributes for concept design 1 outperformed all other competing designs and the performance and NVH attributes were not the only main contributory factors.

Alternative concept design selection methods such as the traditional Pugh decision matrix is commonly used in practice applied to a number of industries due to its ease of use and time efficient process[15]. To compare the results obtained through the application of PROVEN for the air induction system the Pugh approach has been used to evaluate the same three alternative air induction concept designs. Table 5 displays the results obtained using Pugh for the concept design evaluation of the powertrain air induction system.

Table 5: Pugh Matrix: Air Induction System

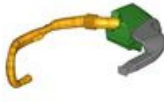| Pugh Concept Selection Chart Template Weighting: 10 = very important 1 = not critical Ratings: -5 = worse, +5 = better		Concept Design 1 Air Box 8L / Dirty Side Duct: 700mm	Concept Design 2 Air Box 8.6L / Dirty Side Duct 600mm	Concept Design 3 Air Box 9L / Dirty Side Duct 800mm
Performance Attributes	Weighting			
Performance (bhp)	10	3	4	4
Weight (Kg)	8	3	4	5
Filtration Efficiency (%)	7	4	5	4
NVH (dB)	10	2	3	3
Package (Volume)	5	4	3	3
Weighted Sum		122	152	153
Ranking		3	2	1

The three candidate design concepts labelled as concepts 1,2 and 3 within Table 5 were evaluated against five performance attribute criteria found within the first column of the Table.

The scoring for each concept design is performed in symbol form, of either positive, negative or neutral scoring. The rating scale used is -5 to +5 with -5 representing poor performance or a score of +5 as the highest performance shown in Table 5.

To better reflect the importance to the decision maker of the assessment criteria used, a weighted criteria in order of importance is defined as part of the Pugh methodology. The more important the criteria the higher the weighting value is given, using a scale of 1-10. Each of the design concepts are scored and multiplied by the criteria weighting values. The total score for each concept is the sum of the weighted scores revealing the ranking for all design alternatives

assessed. In the example shown in Table 5 for the air induction system, concept design 3 scored the highest identifying it as the lead design meeting the key attributes vs. the design alternatives. However if there were no clear winner, this would mean that there is not enough information to discriminate between the options. In such cases it would be necessary to either refine the assessment criteria or to conduct a sensitivity analysis. This can be performed by adjusting the importance numbers by +/-1 and monitoring the ranking of the alternative designs or by adjusting the individual rating values. The air induction example shown in Table 5 showed that concept designs 2 and 3 were very close in the final weighted scores with only one score point separating the two designs. In this instance it would be useful to conduct a sensitivity analysis to demonstrate the effectiveness of the Pugh approach. This is performed by equalising the scores for concept designs 2 and 3 for the highest weighted criteria which in this example was the Performance (bhp) criterion scoring 10. Table 6 shows the score for concept design 2 adjusted from 4 to 5 for the Performance (bhp) criterion resulting in concept design 2 achieving the highest rank position. Although the NVH design criteria also achieved a maximum weighting of 10 the NVH score for concept design 2 did not require adjusting as it performed on par with concept design 3.

Table 6: Pugh Sensitivity - Air Induction System

Pugh Concept Selection Chart Template Weighting: 10 = very important 1 = not critical Ratings: -5 = worse, +5 = better		Concept Design 1 Air Box 8L/ Dirty Side Duct: 700mm	Concept Design 2 Air Box 8.6L/ Dirty Side Duct: 600mm	Concept Design 3 Air Box 9L/ Dirty Side Duct: 800mm
Performance Attributes	**Weighting**			
Performance (bhp)	10	3	4	4
Weight (Kg)	8	3	5	5
Filtration Efficiency (%)	7	4	5	4
NVH (dB)	10	2	3	3
Package (Volume)	5	4	3	3
	Weighted Sum	122	160	153
	Ranking	3	1	2

Although the Pugh approach is widely used as it is easy to understand, simple to apply, and inexpensive there are several drawbacks. If several of the performance attributes happen to tap the same related product performance factor, the method will over-weight (double-count) the importance of those attributes. In addition Beckwith, Neal and Lehmann (2005) show that this method can lead to a bias effect in which a product is inappropriately rated. The author is in agreement with Beckwith, Neal and Lehmann (1975), as 'double-counting' of the attributes assessed was observed during the air induction case study[15]. There was ambiguity in how the concept designs were scored against the five design attributes. One possible reason as to why this was happening was due to the sub-system or component owner's being emotionally attached to a particular design as they believed *'this is the best thing to do'* that had a bearing influence on the scores. This is where subjective assessments had been made with possible pre-conceived assumptions made about the performance of a new component design.

As the Pugh evaluation method has several drawbacks, this potentially carries a level of risk as a non-optimum concept design could be chosen resulting in either late design changes or a compromised product to the customer. The Pugh approach does not translate the final scored concept designs against a value metric related to customer value perception. This is important as the concept development team could quite easily lose sight as to which aspects of the product are vital to the customer. The major under-lying issue observed in using the Pugh approach for the air induction case study was the translation of converting performance values related to a concept design into a rated score between (1-10). This was mainly due to the evaluation process being completely reliant on individuals making their own assessments for their respective sub-system/component open to subjectivity. This is another contributory factor that can lead to the wrong concept design chosen to progress further. In comparison the

PROVEN method uses a data-driven objective approach deriving the final calculated RVI score(s) for each assessed concept design using performance target data attribute bounds.

In practice the PROVEN method identified concept design 1 as the chosen air induction system design to progress further as an optimal level performance was achieved in meeting the five key design criteria.

4.1 New Technology Cost Assessment

Using the three steps defined in Section 2.3(b) to determine a viable business case for competing concept designs, Equations 6 and 7 are used to assess the three alternative air induction system designs. Table 7 displays the net value cost benefit of each design.

Table 7: Concept Design Net Value $

Performance Attributes	$ Value	Concept Design 1 $	Concept Design 2 $	Concept Design 3 $
Performance (bhp)	20 $ per PS	78	61	40
Weight (kg)	16 $ per kg	112	91	99
Filtration Efficiency (%)	14 $ per %	71	98	74
NVH (dB)	20 $ per dB	8	4	11
Package (Volume)	10 $ per mm	50	47	36
Total Attribute Value to company $		318	301	260
System Cost $		200	200	350
Net Value $		118	101	-90

Concept design 1 offered the best value for money as it contributed $118 of net value to the end product in delivering the key performance attributes justifying the overall system cost.

The next best design alternative was concept design 2 that produced a net value of $101 for the company even though the system cost overall was the same as concept design 1. In contrast, concept design 3 offered the least value for money at -$90. This means that not only would it not deliver the key performance attributes as identified in Table 4(a), it also represents a value loss of -$90 to the company that includes the contribution cost of the system at $350.

4.1 *Case study Discussion*

Cooks value equation, is a data-driven method that can be used to determine the importance a single performance attribute serves within the context of a product. It uses key performance criteria as a measure to confirm its worth within the product, relating component performance value for each important performance attribute.   Although the technical cost calculation approach is useful to confirm the value in monetary terms for a particular design, further cost assessments in terms of manufacture, assembly and component part complexity need to be taken into account to determine a total cost evaluation, subject to further research. The initial application of the new PROVEN test-bed to the air induction system case study has provided a useful assessment to determine the most appropriate air induction system to be selected using an objective driven approach against required performance attributes.

5. Conclusions

The defined components of the PROVEN test-bed provide a unique method to objectively confirm the revealed functional value of a concept design. The main benefit of the PROVEN test-bed is the ability to convert performance values of a given technology related to a concept design into a normalised metric (1.0) with a direct comparison made to the target performance attribute bounds. This reduces the overall risk in subjective assessments from being made.

The 1st step of the PROVEN test-bed incorporates the use of Design for Six Sigma that provides a confirmation of the key input critical factors for each sub-system and component to achieve a target output performance. This approach has the ability to identify the key critical input factors of a system, sub-system and component level to achieve target performance attributes. Once these critical input factors are established, the 2nd step is to use preference regression (linear or non-linear equations) that maps sub-system and component aspects to the concept design

selection process allowing for key design trade-off decisions to be made. This provides a translation of attribute performance targets into a normalised metric allowing for a number of concept designs to be compared with each other and therefore simplifying the concept selection process. The 3rd step of the new test-bed is the use of a multi-attribute utility function to provide a numerical data driven evaluation for each concept design. The inter-linking of these key features of the PROVEN test-bed generates a technology value map tailored to specific market requirements. The PROVEN test-bed addresses the key aims of this research by revealing the actual value of each concept design in terms of function and cost as perceived by the customer. It also offers the added benefit in comparing a number of competing concept designs using inherent value engineering equations to accurately assess concept designs against a given set of attributes. The PROVEN test-bed assists with the key design decision trade-off's to be made without degrading the value of the final product in delivering the key performance attributes. This approach provides a means of further reinforcing and linking customer perceived product value with the powertrain concept design technology selection process.

The technology value map generated by the PROVEN test-bed can be used as a generic tool for defining a system design solution to support new product development for any product.

Conflict of interest

None declared.

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