Journal of Aerospace Operations 1 (2012) 3–27
DOI 10.3233/AOP-2011-0011
IOS Press

Value Operations Methodology (VOM) applied to medium-range passenger airliner design

R. Curran[a,*], W. Beelearts[b], T. Abu-Kias[c], M.J.F. Repco[c], Y.L.J. Sprengers[c] and P.N.C.S. van der Zwet[c]

[a]*Chair of Air Transport and Operations and Section Head, Senior Member of AIAA, The Technical University of Delft (TUD), Kluverweg, The Netherlands*

[b]*Assistant Professor, Air Transport and Operations Section, The Technical University of Delft (TUD), Kluverweg, The Netherlands*

[c]*Masters Student, Air Transport and Operations Section, The Technical University of Delft (TUD), Kluverweg, The Netherlands*

Abstract. This paper gives insight in the development of a Value Operations Methodology (VOM) that can be used to support Value Driven Design (VDD). The VOM establishes expressions for operational value levers that are incorporated into a weighted value function. This value function is then used to optimize the design variables that are incorporated into it so that the design process is actively driven by value assessments that provide design decision metrics. However, the VOM is generic in nature and has a much wider range of influence to the design process for any engineering product.

The methodology is verified by means of a case study, analyzing the value difference between the Boeing 737-200, Boeing 737-800, Embraer ERJ-145 and the Airbus 319 as part of a use-case study. In fact, the fundamental conclusion from the work presented is actually that VDD simply promotes the sustained application of the main utility values that were originally recognised but which, due to the complexity of the product and enterprise, tends to be disaggregated into isolated requirements. Ultimately, this leads to optimisation at a sub-system level and that is especially unacceptable for a complex system (with many sub-systems), whereas the re-focus of VOM helps to significantly shift the design effort back to creatively solving the main goal, rather than simply and somewhat robotically making sure the requirements are satisfied. The verification and validation work presented is recognised as indicative but the authors believe that it is extremely significant in pointing towards the potential gains from sustaining a more holistic appraisal and approach through-out the design process. Notwithstanding, the key message of the paper is the need for value modelling within engineering so that we are in control of the consequences of what we are actualising, where value is realised through operational delivery and excellence. This paper has presented a broad methodology in opening up a significantly different approach to aircraft design that is both performance and economics driven while also incorporating other crucial drivers of a much more holistic nature, proactively rather than reactively.

*Corresponding author: R. Curran, Air Transport and Operations (ATO), Faculty of Aerospace Engineering, The Technical University of Delft (TUD), Kluverweg 1, The Netherlands.

ISSN 2211-002X/11/$27.50

1. Introduction

This paper is primarily about the development and application of a Value Operations Methodology (VOM) that can be used to support Value Driven Design (VDD). The methodology is first presented and then verified through comparing existing medium range passenger aircraft using the VOM approach. The main premise of the work is that better design solutions can be developed through a more holistic definition of the criteria to be optimised in the objective function. This broader objective function can be considered to be a value function that typically promotes operational performance and ultimate value to the customer, and is thereby termed VOM.

Section 2 presents the Value Model that is used in the design process; Section 3 then shows how this Value Model is implemented in this case through the Analytic Hierarchy Process. Section 4 contains the results and implied validation of the Value Model where input variables of a Boeing 737-200, Boeing 737-800, Embraer ERJ-145 and Airbus A320 are used. Finally, the paper ends with a discussion of the findings, along with some Conclusions and Recommendations.

2. What is Value Operations Methodology (VOM)

2.1. Value engineering

Value Engineering as a concept was developed at General Electric, USA from the 40's on by Lawrence Miles as a method for considering the customer's willingness to pay for each element of added functionality in a product, as expanded on by through: Value = Function/Price [1]. There have been many further more detailed studies in the area of cost modelling and integration into design but this paper in particular aims to raise value to a less (or not only) financial form and consider its integration into engineering in terms of the context of a customer's value system.

Value Driven Design (VDD) is the process of optimising a product or service through the maximising of a value function that best describes the value added of that product by following the steps of Definition, Analysis, Evaluation, and Improvement [1]. The Value Operations Methodology (VOM) expanded in this paper was an extension of the VDD approach but with the focus on the operational value that in turn requires optimal operation to be understood and utilised in the engineering evaluation process. VOM enables us to drive the design process with a more realistic operations based performance assessment that can pull better technical solutions into the market place.

Following Fishburn [2] Ralph L. Keeney [3] highlighted the similarity between the general structure of a value model and models relating unit selling price and a fixed variable cost of producing the product [1]. The hedonic model proposes that a cost differential between two systems consisting of a set of similar characteristics can be used to value the characteristics, and is based on the concept of a baseline reference price, α. The typical form of the hedonic function that relates the variation in cost to the variation in design characteristics is presented in Eq. 1.

$$\ln(\mathrm{P}_1) = \alpha_1 + \sum_{j=1}^{m} \beta_j x_{ij} + \varepsilon_i \tag{1}$$

where most importantly $j = 1 \ldots m$ is a set of value levers of the system analyzed, P is the price, and β is a weighting factor associated to a defined value lever (or design characteristic) x. This construction is used to define the percentage change in price the stakeholder is willing to pay for an adjustment of any value lever x. The value model is based on Keeney's representation of theorems for quantifying values using utility functions, as proposed by Fishburn, where Keeney defines Fishburn's function as the additive utility function presented in Eq. 2:

$$u(x_1, \ldots\ldots, x_n) = \sum_{i=1}^{N} k_i u_i(x_i) \tag{2}$$

where u_i is an integral attribute utility function for attributes x_i, and k_i are the scaling constants that define a user's value system. It follows that the characterization of a decision problem through a value model leads to a set of goals G_i, $i = 1, \ldots, N$, where the consequences x are part of the attribute X used in measuring the goal G. If it is assumed that the additive utility function does not need to account for interdependencies relating to each consequence x, then there exists a corresponding magnitude of utility u that indicates the value [2]; as shown by Fishburn 1965 [3].

It is concluded that the hedonic model has established: a) the Delta Price Principle: that it is reasonable to relate the price of one design instantiation to another and b) the Additive Utility Principle: that the utility relating to a design instance should be simply accumulated according to the utility each feature or attribute adds.

2.2. Value Operations Methodology (VOM)

Value Driven Design (VDD) [2] is a methodology which promotes the use of a more complete value function as the objective function to be solved through optimisation, rather than using a more limited formulation typically related to some performance metric or through managing the process of meeting requirements. However, this principle can be extended to consider not only the value of today's basic economic drivers but also to incorporate the ultimate value for the customer and even society, depending on who is implementing the Value Operations Methodology (VOM) that focuses on the ultimate value realised in through-life operation.

The contribution of the two principles distilled from the theory presented in the previous Section is fundamental to the theoretical development of VOM, i.e. (a) the Differential Principle and (b) the Additive Principle. The VOM approach builds on both these principles which are intrinsic to the main hypothesis of VOM. This has been incorporated into the fundamental VOM hypothesis as follows:

The true value of an engineering solution is subjective, temporal and of an inherently transient nature, and therefore engineering value analysis and optimisation is more meaningful if formulated as the evaluator's preference for one state over another as a function of the quantitative difference in a number of key value levers related to the operational realisation of the intrinsic value of the product, process or service being considered.

In its most simple form, the implementation of the VOM hypothesis above relates to a sort of binary-gradient based analysis, i.e. a simple positive or negative response to a change in the value system, while gradient based analysis can suggest the degree to which a particular design or attribute is influencing value; rather than trying to actually model each individual subjective element and associated interdependencies. Notwithstanding, the confounding of interdependencies we can also conjecture that in its most simple form the implementation of the VOM hypothesis relates to the aggregation of the value attributed to all the operational characteristics of a design. Furthermore, it is suggested that if secondary influences from one value lever can be incorporated into the primary assessment for another lever then that will further validate the additive value principle.

Relative to a) the Differential Principle, we can say that it is much more reasonable to assess the value of one design instantiation with another in terms of the value gradient relating to the value levers that result in a given delta value from the original state, whether positive or negative. This principle is further expressed in Eq. 3 relative to the value gradients:

$$\vec{\nabla}\nu = \vec{\nabla} f(x, y, z) = \left(\frac{\partial f}{\partial x}, \frac{\partial f}{\partial y}, \frac{\partial f}{\partial z}\right) \tag{3}$$

where the value gradients are associated with a scalar function of the individual value functions or value levers (*x,y,z*). The Differential Principle suggests the use of both deltas and more fundamentally the gradients which give rise to those deltas. Equation 3 proposes that any value gradient or gradient vector field, $\vec{\nabla}\nu$, of the scalar function, $f(x, y, z)$ is indeed a function of the value gradients or partial derivatives $\left(\frac{\partial f}{\partial x}, \frac{\partial f}{\partial y}, \frac{\partial f}{\partial z}\right)$; which are associated with the value model (scalar function) being a function of the individual value functions or value levers ( ). Therefore, it can then be deduced that this can be expressed in terms of the standard vectors ($\hat{\text{i}}$, $\hat{\text{j}}$ and $\hat{\text{k}}$) associated with the individual value functions (x, y, z) and their partial derivatives, as shown in Eq. 4:

$$\left(\frac{\partial f}{\partial x}\hat{\mathrm{I}} + \frac{\partial f}{\partial y}\hat{\mathrm{J}} + \frac{\partial f}{\partial z}\hat{\mathrm{K}}\right) \tag{4}$$

Therefore, a fundamental consequence of the Differential Principle construct has led directly to the rational for the 'already anticipated' Additive Principle, where value analysis is carried out by accumulating the individual contributions from the various contributing value levers.

Furthermore, relative to b) the Additive Principle, we can say that it is reasonable to asses the value delta presented in Eq. 4 as an aggregration of all of the individual levers' delta values. Consequently, this principle is further expressed in Eq. 5:

$$\triangle V(x_i, \ldots, x_n) = \sum_{i=1}^{N} \alpha_i \sum_{j=1}^{M} \omega_j \frac{(\nu(x_{ij}))_{end}}{(\nu(x_{ij}))_{start}} + \varepsilon_{ij} \Bigg| \tag{5}$$

Where a change in value _V is caused by a change in a set of associated value levers *xi*, when moving from some start-state to some new end-state. Each value lever of the set $i = 1 \ldots N$ has an associated scaling factor ai and error eiand is in turn defined by a subset of lower level value parameters, *xji* for $j = 1 \ldots M$ and associated scaling factor ω_j, that describe the causal nature of each of each driver. The establishment of the lower level value parameter functions are carried out using the Genetic-Causal Approach (GCA) presented by Curran et al. [55]. The GCA was first developed with respect to cost modelling but is particularly well suited to the evaluation of any value driver and is based on two fundamental scientific principles: a) the Genetic Principle: categorizing drivers and parameters into sets of a similar nature; and b) the Causal Principle: formalizing relationships explicitly only where cause and effect is satisfied.

In giving form to VOM through our use-case of an aircraft passenger jet, a model is proposed that captures the value of the aircraft design choices in terms of the operational impact and realisation through explicit value-adding criteria. The following value levers were utilised by the authors in a differential-additive valuation manner as shown in Eq. 6. These value levers are subjective in nature and should be selected by the user (as well as the weightings) but the authors included: Cost efficiency C (revenue/cost), Utilization U, Maintainability M, Environmental Quality E, and Passenger Satisfaction P. The methodology also proposes to use Safety S as a value lever as well as considering an error ε, although that is not yet incorporated in the presented work. The differential principle is respected by the left-hand side of the equation while the additive principle is respected by the right-hand side of the equation.

$$\Delta V = \alpha_C(c_1/c_0) + \alpha_U(U_1/U_0) + \alpha_M(M_1/M_0) + \alpha_E(E_1/E_0) + \alpha_P(P_1/P_0) + (\alpha_S(S_1/S_0) + \varepsilon) \tag{6}$$

The value levers influence on one another is modeled with reference to Asavathiratham's influence modeling [4]. The value levers consist of the sum of specific system characteristics deltas multiplied by the corresponding weighing factors. The system-characteristic deltas are based on a reference aircraft's characteristics, relative to those of the corresponding aircraft under consideration. The *Costing* value lever is worked out in detail as shown in Eq. 7.

$$\begin{aligned} C = {} & \omega_1 \cdot d[\text{DepreciationIOC}] + \omega_2 \cdot d[\text{Ticket/sales}] + \omega_3 \cdot d[\text{Admin/other}] + \omega_4 \cdot d[\text{Staff}] \\ & + \omega_5 \cdot d[\text{Maintenance}] + \omega_6 \cdot d[\text{Fuel}] + \omega_7 \cdot d[\text{Crew}] + \omega_8 \cdot d[\text{Interest}] + \omega_9 \cdot d[\text{Insurance}] \\ & + \omega_{10} \cdot d[\text{DepreciationDOC}] + \omega_{11} \cdot d[\text{Airport}] + \omega_{12} \cdot d[\text{Navigation}] + \omega_{13} \cdot d[\text{PaxServices}] \end{aligned} \tag{7}$$

where *C* is the *Costing* value lever variable and represents the number of value points corresponding to the cost of the aircraft under consideration, ω are the weight factors corresponding to the individual deltas, d[Depreciation IOC] is the delta of the cost depreciation of the indirect operating cost IOC, d[Ticket/sales] represents the ticket/sales cost delta, d[Admin/other] defines the administration and other costs delta, d[Staff] is the staff cost delta, d[Maintenance] is the maintenance cost delta, d[Fuel] the fuel cost delta, d[Crew] Flight crew cost delta, d[Interest] is the interest cost delta, d[Insurance] defines the insurance cost delta, d[Depreciation DOC] defines the depreciation of the direct operating cost delta, d[Airport] is the delta of the airport costs, d[Navigation] is the delta of the navigation costs and d[Pax Services] defines the passenger services cost delta. The value model is based on the input of two aircraft, a reference aircraft as a benchmark (subscript *0*) and the data of the aircraft under consideration (subscript *1*), where the aim of the value model is to return the value of the aircraft under consideration with respect to the benchmark aircraft.

The second level weighting factors, ω_{1-13}, in Eq. 7 indicates how much value can be obtained by an improvement of the design. In this Equation all deltas are the differentials of the aircrafts cost and the reference aircraft cost. The deltas are defined in order to capture the aircrafts value in comparison to the reference aircraft data. For example in the cost variable *C*, the delta of the Maintenance cost, d[Maintenance], can be defined as the maintenance cost of the reference aircraft divided by the maintenance cost of the aircraft under consideration, d[maintenance] = (reference aircraft maintenance cost)/(aircraft maintenance cost). A low maintenance cost of the aircraft under consideration corresponds to a high number of VP's coming out of the value model. The influence model of the total cost, gives an overview of the sub variables influences on the value lever cost.

The aircraft reference data influences the cost variable C indirectly. A couple of indirect relations between aircraft reference data and the cost variable C are given here. A lower weight of the aircraft under consideration in comparison to the reference aircraft decreases the airport cost, since the airport cost is a function of aircraft weight. The airport cost in his turn directly influences the cost variable C, see Eq. 7 and the cost influence model in Eq. 8. A lower seat number of the aircraft under consideration in comparison to the reference aircraft decreases the crew cost, since less crew is required. The number of crew personnel required directly influences the cost variable C, see Eq. 7 and the cost influence model. The material used influences the weight. Lower weight of the aircraft in comparison with the reference aircraft corresponds to a lower fuel use, since there is less energy needed to keep the aircraft in the air. The fuel use influences the cost variable directly; as demonstrated in Eq. 7 and the cost influence model. The catering equipment sizes and weight of the aircraft under consideration, in comparison to the reference aircraft, influence the overall aircraft weight and size. An average lower cruise mach in comparison to the reference aircraft increases the fuel efficiency. Fuel efficient aircraft correspond to lower fuel cost for the airliner. The fuel cost is directly related to the Costing lever *C* as mentioned above.

2.3. Analytical hierarchy implementation of VOM

The trade-off theory related to Analytic Hierarchy Process (AHP) developed by Thomas L. Saaty [5] is used to produce a figure of merit for each design option; the process being described as the following:

1. Describe in summary form the alternatives under consideration.
2. Develop a set of high-level evaluation objectives; for example, science data return national prestige, technology advancement, etc.
3. Decompose each hi-level evaluation objective into a hierarchy of evaluation attributes that clarify the meaning of the objective.
4. Determine, generally by conducting structured interviews with selected individuals ("experts") or by having them fill out structured questionnaires, the relative importance of the evaluation objectives and attributes through pair-wise comparisons.
5. Have each evaluator make separate pair-wise comparisons of the alternatives with respect to each evaluation attribute. These subjective evaluations are the raw data inputs to a separately developed AHP program, which produces a single figure of merit for each alternative. This figure of merit is based on relative weight determined by the evaluators themselves.
6. Iterate the questionnaire and AHP evaluation process until a consensus ranking of the alternative is achieved.

Essentially, the AHP approach adopted in this example of VOM implementation made it possible to consider the best design options in a more realistic trade-off based on criteria with unequal weight and more qualitative independent variables. The first step is to select the trade criteria and to expand the definition to incorporate the most relevant drivers or parameters. After initial selection the down-selection is facilitated by making pair-wise comparisons between the selected criteria, where each comparison determines the degree of importance each criterion has over the other in relation to the design traded-off. The numerical scale used for the comparisons ran from 1 to 9 (to give an increased fidelity over the 4 increment Likert scale for example), where the reciprocal values corresponded to 1/9 to 1. All n criteria were compared to one-other and the results structured in matrix form, resulting in an $n \times n$ comparison matrix (see Table 1); where, two parameters are of particular importance: the eigenvalue and the eigenvector. Firstly, the eigenvalues of a matrix are obtained through solving Eq. 8 for λ; where A is the comparison matrix, I is the identity matrix and λ is the eigenvalue [6]. The sum of all eigenvalues is equal to the sum of the elements on the main diagonal of the matrix, called the trace of the matrix [6].

$$\det(A - I\lambda) = 0 \tag{8}$$

Secondly, the eigenvector of a matrix is obtained using Eq. 9 in which x is the eigenvector corresponding to a particular eigenvalue λ. The normalized eigenvector is obtained by dividing every value in the eigenvector by the sum of all items [6].

Table 1
Example comparison matrix

	Criterion 1	Criterion 2	..	Criterion n	Eigenvector	Consistency Ratio
Criterion 1	W_1/W_1	W_1/W_2	..	W_1/W_n	v_1	CR
Criterion 2	W_2/W_1	W_2/W_2	..	W_2/W_n	v_2	
..	..	..		..	..	
Criterion n	W_n/W_1	W_n/W_2	..	W_n/W_n	v_n	

$$Ax = \lambda x \overset{\Delta}{\rightarrow} (A - \lambda I)x = 0 \tag{9}$$

Regarding the comparison matrix, Saaty [6] states that if the comparisons are ‘perfect’ this will result in a comparison matrix where each row is a constant multiple of the first row, where the matrix has a rank of one and thus results in only one eigenvalue that is non-zero. When the normalized eigenvector belonging to that non-zero eigenvalue is obtained, the values in the eigenvector ($\bar{V} = [v_1, v_2, \ldots, v_n]^{\mathrm{T}}$) represent the weighting factor of each criterion [7] are calculated.

However, in order to take into account that the comparisons are performed by an inherently subjective group of actors who compare items that are not necessarily easy to quantify there will almost certainly be inconsistencies (i.e. human errors) in the comparisons. Saaty [8] has shown that the eigenvalue approach he proposed is not only still valid for inconsistent matrices but contends that it is also the only valid method for deriving the priority vector from a pair-wise comparison matrix. It follows that any inconsistency in the matrix will show up in the Consistency Ratio (CR); as inferred by Eq. 10 where *CI* is the Consistency Index and *RI* is the Random Consistency Index. The value of the CI is obtained using Eq. 11, in which λ_{max} is the largest eigenvalue of the $n \times n$ comparison matrix [9]. Furthermore, the value for *RI* is obtained from Table 2, which presents the result for the *CI* value of a $n \times n$ matrix when the average value is taken from 500 computations on reciprocal (comparison) matrices with randomly chosen inputs(as is explained by Saaty [9]).

$$CR = \frac{CI}{RI}, \text{ where: } CI = \frac{\lambda_{\max} - n}{n - 1} \qquad (10) \,\&\, (11)$$

In the case that the comparisons relate perfectly to each other, the value of CI and therefore CR will be zero. This is a consequence of the fact that for a perfect comparison there is only one eigenvalue, which is equal to the trace of the matrix and thus $\lambda_{\max}$ will be equal to n. In the case of inconsistencies, the comparison matrix will not be perfect and $\lambda_{\max}$ will differ from n; where $\lambda_{\max}$ is obtained from Eq. 11 and results in a non-zero value of CR. In order to know if the results are still valid, Saaty [9] presents the basic rule of the value of CR not exceeding 0.10 - by much. Essentially, if CR is larger than 0.10 the comparison matrix should be looked at again and should be updated.

Subsequent to the weighting factors for the trade criteria, and sub-criteria, being determined, the design options are evaluated according to those metrics. Pair-wise comparisons are carried out between the different options for each criterion and the results are then evaluated in a comparison matrix (including one for every criterion). The normalized eigenvector of these matrices gives the score for each particular design option relating to the corresponding trade criterion (*C1* to C*n* in Fig. 1). The overall figure of merit was then obtained by first multiplying the scores for each criterion with the corresponding weighting factors (*W1* to W*n*), which were obtained during the comparison process through the trade criteria, and then adding the results on each trade criterion for each design option. The rational is then that the option with the highest value is the winner for this trade-off methodology.

Table 2
Random consistency Index (RI) values for reciprocal (comparison) matrices of size $n \times n$

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

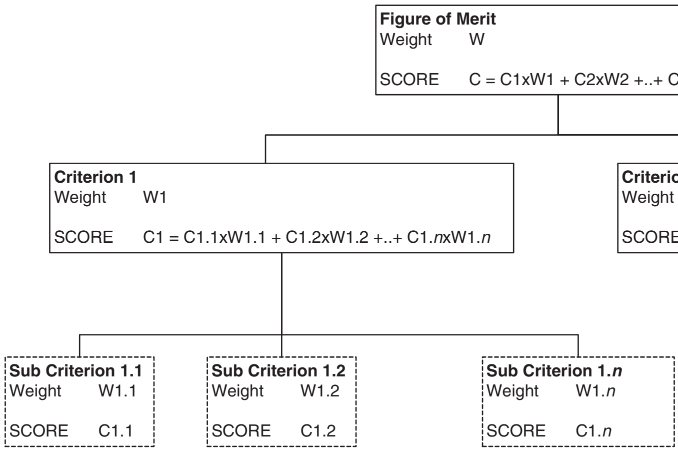

Fig. 1. Calculation of the Figure of Merit.

It should be noted that when considering the ‘Figure of Merit’ shown in Fig. 1 the following restrictions apply in Eqs. 12 and 13:

$$W = W1 + W2 + .. + Wn = 1 \quad \& \qquad W1 = W1 \cdot 1 + W1 \cdot 2 + \cdots + W1 \cdot n \qquad (12)\ \&\ (13)$$

By using this method the designers who have the best knowledge relating to their part of the design will perform the trade-off that relates to their particular design options and expertise. Subsequent to each trade-off, the presentation of the expert results to other group members can be simply carried out to ensure that everyone’s individual interpretation of the trade criteria tested, is as generic as possible and less open to personal preference.

3. Creating the airliner VOM value model

The example VOM model presented here-on is based on the main attributes of value: Cost, Environmental Quality, Passenger Satisfaction, Utilization and Maintainability, while Safety was omitted in this study – see also Eq. 3. The design requirements [10] for the airliner utilised in the validation study highlighted that sustainability targets (which were consequently set very high) and also the economics of the design should be optimized from a value perspective. Since most value for the airline is typically generated by keeping the costs low and revenue high, it was important that the aircraft would be operational as often as possible and at little cost. Consequently, Utilization and Maintainability were both given a more average but still significant weighting. A reduction in Direct Operating Cost for the airline will also enable the airline to offer a lower ticket price that is also beneficial for the passengers. However, the market needs were aligned to the Passenger Satisfaction (rather than the airline) and only added value for the passenger in the current limited implementation of the VOM methodology; whereas meeting passenger needs can lead to greater market share, long term branding and customer loyalty. Therefore, Passenger Satisfaction was rated at a lower level than Cost or Sustainability is considered to be of less importance in the design of an airliner, because passengers will continue to fly simply because there is no competitive alternative for the airliner. The resulting value model is presented in Table 3, relating to Eq. 5. This allocation of value is intentionally set to be challenging to current short-term financial thinking which would automatically put cost automatically at say 60–80%.

Table 3
Airliner design Value Model – The division of total value

Value in Airliner design	%
Cost	30
Environmental quality	30
Passenger satisfaction	10
Utilization	15
Maintainability	15

The hypothetical approach stipulated in Table 1 underlies the fundamental shift in driving the design process with an operational value analysis assessment (VOM), which is better positioned to also anticipate future economic constraints through its more holistic approach. However, Cost, Utilisation and Maintainability are all of a primarily financial nature and total 60%, while Passenger satisfaction is also highly interdependent and even Environment starts to become a customer consideration! Notwithstanding, Environmental Quality has been set at a very challenging 30% although airlines and aircraft manufacturers would probably set this no higher than 5%, over and above the other four criteria. In fact, this issue bears comparison with Safety and Cost where the safety or cost drivers are not so much incorporated into the design variables and parameters but are seen as targets to be met in a rather binary manner, i.e. as mathematical constraints. Such constraints are the lowest form of design decision making and in effect remove the potential for that driver to actively influence the evolution of a design so we end up with a more trial and error method. On the contrary, VOM aims to incorporate the influence and potential impact of all design parameters so that the design process becomes leaner and achieves a more globally optimal solution.

3.1. Costing

Indirect Operating Costs (IOC) relate to costs for the airline that are not influenced by using the airliner, while Direct Operating Costs (DOC) relate directly to the utilisation of the airliner. A review of the general airliner cost models from Boeing [11], ICAO [12], Martinair model [13],Boeing/MIT [14] and an MIT [15] model resulted in the 13 items incorporated into Table 4. These percentages define the value that is allocated to the reduction of each cost driver or value lever.

3.2. Utilization

It has already been suggested that the elements that determine an aircraft's utilization are then fundamentally linked to how much time the aircraft is available to generate revenue. According to Doganis [16], short haul fights generate more profit than long haul flights (while short haul flights are more dependant on take-off and landing) and based on this it is determined that the stage length should be relatively small in calculating Utilization. Similarly, flights per day and ultimately block hours per aircraft should be as high as possible while the turnaround time should be as low as possible; the latter being treated as necessary non-value-added effort. Since turnaround time is the only item which relates to an event where there are no passengers on board (i.e. no revenue is generated off them) this item is assigned the highest weighting factor in Table 5.

3.3. Maintainability

Maintainability is defined as all aspects of an airliner that relate to the maintenance and producability. Research into the life cycle cost of an airliner [2] shows that there are six key aspects that influence the cost. One of these aspects is the cost of using the airliner, which does not fall under the definition of maintainability in the presented model and therefore is not included as Cost is the lever that incorporates this aspect; while the remaining five aspects are presented in Table 6.

3.4. Environmental quality

The definition of Environmental Quality was separated into three categories relating to: Flight Procedures, Aircraft and Engine Design, and Production. The Production was determined to be 20% while the subdivision of the Flight Procedures and Aircraft and Engine Design part was apportioned according to the guidelines of Vital et al. [17]; who estimate that improved ATC procedures and aircraft and engine design can lead to a fuel consumption reduction of 12%, 20% and 20% respectively, or 52% in

Table 4
Allocation of the weighting factors for the Cost value lever

Cost	%
IOC	
Depreciation	9,3
Ticket/Sales	11,1
Admin/other	6,5
Staff	3,4
DOC	
Maintenance	9,3
Fuel	16,0
Crew	11,8
Interest	7,2
Insurance	0,8
Depreciation	6,9
Airport	6,0
Navigation	4,4
Passenger services	7,3

Table 5
Allocation of the weighting factors for the Utilization value lever

Utilization	%
Daily hours	20
Block hours	20
Stage length	20
Turnaround time	40

Table 6
Allocation of the weighting factors for the Maintainability value lever

Maintainability	%
R&D	13,6
Production	54,5
Ground equipment + initial spares	15,9
Special construction	11,4
Disposal	4,6

total. Consequently, Flight Procedures (12%) and Aircraft and Engine Design (40%) were allocated these weighting factors. Each of the three categories was then subsequently decomposed into sub-drivers.

The impact of optimal flight procedures (Taxiing, Take-off, Cruise and Landing) was determined by how much fuel was burned during each stage. An analysis solution using data from Ruijgrok [18], H. Nojoumi, I. Dincer, G.F. Naterer [19], smartcockpit [20] and RITA [21] that related engine thrust settings to time yielded the various contributions. The Aircraft and Engine Design items division was based on the requirements for noise and pollution reduction, and these are therefore determined to be evenly important. The further subdivision of the pollutants was based on the emission index (EI) of the different pollutants [18], which indicates the amount of pollutant produced for every kg of fuel burned. Certain indexes depend on the thrust setting and for these items the value for the time-weighted average thrust setting during fight was used; as well as the assumption of a linear relationship between the thrust setting and the change from the lowest to the highest EI number of the relevant pollutants. Finally, the division of the importance of the items in the production phase was said to be evenly divided; as both a reduction in pollution during production and a better recyclability have a great impact to the sustainability of the design. This all resulted in the following weighting factors shown in Table 7.

3.5. Passenger satisfaction

The evaluation of Passenger Satisfaction was based on the Contingent Valuation method, which features a market survey that determines how people value certain aspects. The market survey was carried out at the University, thereby providing a limited input of the market requirements for the value model that should be made more generic in future to improve external validity. Notwithstanding, the values gained are presented in Table 8 and are seen to be reasonable. The weighing factors are also based on the market need survey from which it was found that factors relating to Passenger Satisfaction were rated at 19% for speed, 5% for onboard service and 4% for the comfort of the aircraft. These percentages were scaled to 100% and each item further subdivided according to the onboard services and entertainment, from which it was concluded that passengers rated services (5% Not Important) as more important than the entertainment (28% Not Important).

Speed was determined by the way in which the boarding was carried out and the time required for the whole procedure of boarding and check-in, which also influences the turnaround time. Consequently, the Boarding option is considered to have a smaller impact on the speed (30%) than the Boarding/Check-in time (70%). In the Service category most services were judged to be evenly important, while the entertainment was of less importance while comfort was only determined as a function of the seat pitch. It is interesting to note that currently the seat pitch has a weighting factor of 14% while shopping is only 2%; since the survey yielded that passengers find service more important than comfort. It is concluded

Table 7
Allocation of the weighting factors for the Environmental Quality value levers

Environmental Quality	%
Flight procedures	
Taxiing	0,1
Take-off	0,5
Cruise	17,3
Landing	0,6
A/C and engine	
CO2	21,7
H2O	8,6
CO2	0,2
UHC	0,1
Soot	0,0
Nox	0,1
Sox	0,0
Noise	30,8
Production	
Recycle	10
Pollution during production	10

that service should be considered as a total package that needs to include all items related to service and cannot be easily disaggregated, unless a much more detailed survey is carried out.

4. Airliner value model implementation through AHP

The next step in the design process is to use the Value Model developed to make the design choices for the airliner, e.g. for engine type etc, where the trade criteria consist of: Regulations; Requirements; and Value. The Regulations to be complied with are those set by the authorities while the requirements are identified from the requirements analysis and finally, the value metrics come from the Value Model. In the trade-off process, the Value Model is used to indicate how each design option compares to the other regarding the inherent amount of value calculated for that option and Fig. 2 provides the overview of the calculation of the figure of merit for the airliner components.

The determination of the weights for the various trade criteria was carried out by making pair-wise comparisons between the criteria on the basis of how much more (or less) important each criterion was over the others. The results were then put into a comparison matrix and the eigenvector calculated in order to provides the weighting factors (W1, W2 and W3) for each criterion. This process is repeated for each airliner component that is to be traded off, i.e. Fuselage layout, Wing type, Stability configuration, Engine type, Fuel type, Main material, Braking system, Power Ground Operations system, Taxiing method and Fuel Tank location.

An example of the calculation of the weights for the engine type is provided in Table 9, where the Requirements were judged to be 5 times more important than the Regulations, and Value 3 times more important than the regulations. This is reasonable also as all engines under consideration must be certified

Table 8
Allocation of the weighting factors for the Passenger Satisfaction value lever

Market requirements	%
Speed	
Boarding options	20,4
Boarding/Check-in time	47,5
Services	
Hand baggage size	2,4
Hand baggage weight	2,4
Baggage size	2,4
Baggage weight	2,4
On board entertainment	1,0
Catering	2,4
Shopping	2,4
Seat reservation	2,4
Comfort	
Seat pitch	14,3

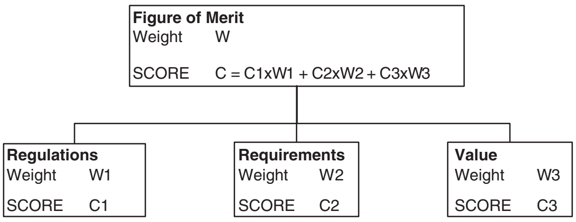

Fig. 2. Calculation of the Figure of Merit applied to airliner components.

by the ruling authorities and are a vital component when design (performance) requirements are being considered. It is also a good example of the Value Operations Methodology working in tandem with recognised approaches but augmenting them rather than only satisfying requirements and regulations. The resulting matrix with all of the reciprocal values is a 3×3 matrix from which the eigenvalues are calculated according to Eq. 14:

$$\det(A - I\lambda) = \det \begin{vmatrix} 1-\lambda & 1/5 & 1/3 \\ 5 & 1-\lambda & 3 \\ 3 & 1/3 & 1-\lambda \end{vmatrix} = -\lambda^3 + 3\lambda^2 + \frac{16}{45} = 0. \tag{14}$$

which has only one real solution: $\lambda = 0.0385$. With reference to Eq. 10 this results in a Consistency Index of: $CI = \frac{3.0385-3}{3-1} = 0.0192$, and consequently, with reference to Eq. 9 and Table 2, a Consistency Ratio of: $CR = \frac{0.0192}{0.58} = 0.033$. The CR value of 0.033 is less than 0.10 and therefore the results from the matrix are considered to be valid and the pair-wise comparison consistent. Using Eq. 14 and solving for the non-trivial solution (in this case done by using the "*eig*" command in MATLAB) the eigenvector was obtained so that the normalization of the eigenvector results in the eigenvectors presented in Table 9.

Table 9
Example comparison matrix

Engine type	Regulations	Requirements	Value	Eigenvector	Consistency ratio	Weights
Regulations	1	1/5	1/3	0.106	0.033	0
Requirements	5	1	3	0.633		0.739
Value	3	1/3	1	0.261		0.261

In this case, the weight allocated to Regulations was ultimately considered to be negligible as it was so low and its impact was added to the Requirements for the optimisation process, although compliance was ultimately checked at the end.

Relative to the trade-off weights allocated to the other components, for the fuselage design the regulations and requirements were of less impact as in the more detailed design all regulations and requirements are naturally adhered to and checked for compliance in every design, essentially acting as optimisation constraints. Also in the wing design it was possible to implement the design in such a way that the wing adhered to all regulations and requirements and therefore also in this design the opportunity to add value was considered the only optimisation criteria of importance.

The selection of which material to use for different parts of the aircraft was also only based on the possibility to add value as the regulations and requirements did not apply directly to the materials. Regulations are important in the certification of the aerospace materials, but once the materials are certified for the use in an aircraft this aspect is no longer a decisive aspect. In the design trade-off for the braking systems the only criteria utilised related to Value as in a simplified process the regulations do not apply to how the braking is done but just to meeting the requirement. The requirements do not apply to the choice of which power system for ground operations, while the regulations do apply since the current APU system most airliners operate will probably be obsolete in the near future. The taxiing system was again fully determined by Value although all options were checked for their reduced impact on the environment. In the trade-off for the location of the fuel tanks the regulations were also negligible since every possible location under consideration was already used in practise and therefore already determined to be within the regulations.

The final weightings utilized for all the key design options are summarised in Table 10. Having determined the weightings for the trade criteria the determination of the figure of merit was performed as is presented in Fig. 2, with a figure of merit being obtained for each individual design option for each airliner component. The determination of the figures of merit was again performed by using pair-wise comparisons and the resulting eigenvector. For the regulations and requirements criteria the design options were compared against each other so that a judgement could be made on how capable the design options were with respect to the others in adhering to the regulations or helping to achieve the requirements. For the Value element of the figure of merit the Value Model was used to compare how each design options performs compared to the other alternatives or options. Ultimately, when all items of the value model that related to the design option were filled-in the Model would return a total amalgamated value according to Eq. 4, which would then be used to evaluate one design option is over the other. These comparative ratings are then put into the separate comparison matrices for Regulations, Requirements and Value, the eigenvalues obtained and the consistency ratios are checked.

Table 10
Weight factors of each trade criteria for each airliner component

	Regulations	Requirements	Value
Fuselage layout	0	0	1
Wing type	0	0	1
Stability configuration	0	0	1
Engine type	0	0.739	0.261
Fuel type	0.429	0.429	0.142
Main material	0	0	1
Braking system	0	0	1
Power G.O. system	0.788	0	0.212
Taxiing method	0	0	1
Fuel tank location	0	0	1

5. Case study results and validation

The theoretical intention of the application to mid-range passenger airlines was also to establish the validity of the VOM approach by comparing three competing aircraft with respect to an older generation aircraft. Consequently, the Boeing 737–200 operated by Ryanair was chosen as reference baseline aircraft to be compared against a next generation Boeing 737–800 also operated by Ryanair, an Embraer ERJ-145 operated by ExpressJet and an Airbus A320 is operated by EasyJet; with the input data and results presented in Tables 11 and 12 respectively.

5.1. Comparison first to next generation aircraft family model (737–200/800)

In the first case the older Boeing 737–200 operated from 1994 to 2005 by Ryanair [22, 23] was compared to a next-generation Boeing 737–800 NG currently operated by Ryanair [24, 25].

5.1.1. Aircraft cost

Cost control and cost breakdown is difficult to measure between a range of models as it is Airline dependent and often differently budgeted. However, the efficiency of the operational processes of an Airline is reflected in the Total Operating Costs (TOC), which can be found in the Airliner's annual papers, and therefore by using the same airliner, i.e. Ryanair, one can compare the model for two instances of the same operational and cost environment. In 1999 more than 80% of the Ryanair total fleet of 22 aircraft [23] consisted of B737–200 aircraft [26] while in 2009 the fleet consisted only of 181[23] next generation B737–800 aircraft [26].

The interest costs and insurance costs are dependent on the list price of the aircraft where the list price is recalculated to its Net Present Value (NPV) by taking inflation into account. Consequently, the NPV of a Boeing 737–200 was calculated to be 55.79 m$ [27], while the NPV of a Boeing 737–800 was calculated to be 75.30 m$ [28]. Consequently, the VOM approach has assessed that the 200 variant was 35% cheaper than the next generation 800 model in today's US dollars; with all the operating cost factors expressed in Euros per ASK.

Table 11

Input data for comparitive VOM value analysis for medium range commercial jet airliners

Model	Boeing 737-200 (1999)			
Carrier	Rynair			
Fleet (#AC)	22			
ASK (millions)	2608.58			
Year	1999	2009	2009/ASK	
	M€	M€	M€	
Total Operating expenses	227.898	295.812	0.1134	100.00
Fuel (-9.68%)	36.554	47.447	0.0182	16.04
Staff (-385.78%)	39.834	51.705	0.0198	17.48
Depreciation (-433.26%)	36.209	46.999	0.0180	15.89
Maintenance (-575.28%)	11.961	15.525	0.0060	5.25
Marketing (-7176.48%)	24.602	31.933	0.0122	10.80
Renting (-40.3%)	2.909	3.776	0.0014	1.28
Route (-173.87%)	20.806	27.006	0.0104	9.13
Airport fees (-147.01%)	29.036	37.689	0.0144	12.74
Other (-604.48%)	25.987	33.731	0.0129	11.40
	M€			
Aircraft Cost (Depreciation +	39.118	50.775	0.0195	17.16%
Purchase Cost		55.79		
Interest	1			
Insurance	1			
Range (nm) max payload	2645			
Passengers (29 inch)	130			
(De-)Boarding% TAT	55.17%			
Turnaround time				
Utilization (hours/day)	6.470			
Average stage length (miles)	339			
TSFC (lb/lb/hr)	0.779			
FC/seat (kg/hr/seat)	23.22			
Noise (EPNdB)	95.3			
Clmax TO@MTOW	2.07			
Clmax LAND@MLW	2.73			
T/W	0.277			
Hold volume/Pax [m³]	0.19			

Model	Boeing 737-800 (2009)			
Carrier	Ryanair			
Fleet (#AC)	181			
ASK (millions)	75804.13			
Year	2009	2009/ASK		Change
	M€	M€		%
Total Operating expenses	2.849.334	0.038	100.00	
Fuel (-9.68%)	1.257.062	0.0166	44.12	-9,68
Staff (-385.78%)	309.296	0.0041	10.86	-385,78
Depreciation (-433.26%)	256.117	0.0034	8.99	-433,26
Maintenance (-575.28%)	66.811	0.0009	2.34	-575,28
Marketing (-7176.48%)	12.753	0.0002	0.45	-7176,48
Renting (-40.3%)	78.209	0.0010	2.74	-40,30
Route (-173.87%)	286.559	0.0038	10.06	-173,87
Airport fees (-147.01%)	443.387	0.0058	15.56	-147,01
Other (-604.48%)	139.140	0.0018	4.88	-604,48
	M€			
Aircraft Cost (Depreciation +	334.33	0.004	11.7	-341,34
Purchase Cost	75.30			34,97
Interest	1.350			
Insurance	1.350			
Range (nm) max payload	4000			51,23
Passengers (29 inch)	189			45,38
(De-)Boarding% TAT	55.17%			
Turnaround time	25.04%			25,04
Utilization (hours/day)	9.59			48,22
Average stage length (miles)	654			92,92
TSFC (lb/lb/hr)	0.56			28,11
FC/seat (kg/hr/seat)	14.73			36,55
Noise (EPNdB)	80			16,05
Clmax TO@MTOW	2.20			6,28
Clmax LAND@MLW	2.96			8,42
T/W	0.279			0,69
Hold volume/Pax [m³]	0.25			31,58

Model	Embraer ERJ 145(XR)					
Carrier	ExpressJet					
Fleet (#AC)	244					
ASK (millions)	20287.39					
Year	2008	2009	2009	2009/ASK		Change
	M$	M$	M€	M€		%
Total Operating expenses	1.434.7	1.436.0	1.031.8	0.0509	100.00	
Fuel (-9.68%)	228.0	228.2	164.0	0.0081	15.89	-125,04
Staff (-385.78%)	397.5	397.9	285.9	0.0141	27.71	-40,66
Depreciation (-433.26%)	33.4	33.4	24.0	0.0012	2.33	-1421,67
Maintenance (-575.28%)	197.4	197.6	142.0	0.0070	13.76	17,58
Marketing (-7176.48%)	25.7	25.7	18.5	0.0009	1.79	-1243,66
Renting (-40.3%)	197.1	197.3	141.8	0.0070	13.74	382,72
Route (-173.87%)	96.2	96.3	69.2	0.0034	6.71	-203,57
Airport fees (-147.01%)	59.6	59.7	42.9	0.0021	4.15	-583,82
Other (-604.48%)	199.8	200.0	143.7	0.0071	13.93	-82,56
	M€					
Aircraft Cost (Depreciation +	230.5	230.7	165.8	0.008	16.1%	-138,21
Purchase Cost		23.5	16.9			-69,73
Interest	0.303					
Insurance	0.303					
Range (nm) max payload	1550					-41,40
Passengers (29 inch)	50					-61,54
(De-)Boarding% TAT	55.17%					
Turnaround time	-33.95%					-33,95
Utilization (hours/day)	8.5					31,38
Average stage length (miles)	594					75,22
TSFC (lb/lb/hr)	0.625					19,77
FC/seat (kg/hr/seat)	24.70					-6,39
Noise (EPNdB)	77.9					18,26
Clmax TO@MTOW	2.11					1,93
Clmax LAND@MLW	2.83					3,66
T/W	0.320					15,48
Hold volume/Pax [m³]	0.184					-3,16

Model	Airbus A320 family				
Carrier	EasyJet				
Fleet (#AC)	181				
ASK (millions)	58165				
Year	2009	2009	2009/ASK		Change
	M£	M€	0		%
Total Operating expenses	2.623.1	2.884.7	0.0496	100	
Fuel (-9.68%)	807.2	887.7	0.0153	30.77	-19 18
Staff (-385.78%)	306.6	337.2	0.0058	11.69	-241.92
Depreciation (-433.26%)	55.4	60.9	0.0010	2.11	-1620.07
Maintenance (-575.28%)	161.6	177.7	0.0031	6.16	-94 79
Marketing (-7176.48%)	47.0	51.7	0.0009	1.79	-1277 56
Renting (-40.3%)	116.2	127.8	0.0022	4.43	51 78
Route (-173.87%)	232.3	255.5	0.0044	8.86	-135 71
Airport fees (-147.01%)	737.4	811.0	0.0139	28.11	-3 63
Other (-604.48%)	159.4	175.3	0.0030	6.08	-329.13
	M$	M€			
Aircraft Cost (Depreciation +		188.7	0.003	6.54	-499.93
Purchase Cost	70.3	50.56			-9 38
Interest	0.906				
Insurance	0.906				
Range (nm) max payload	4100				55.01
Passengers (29 inch)	160				23.08
(De-)Boarding% TAT	55.17%				
Turnaround time	12.73%				12.73
Utilization (hours/day)	11.0				70.02
Average stage length (miles)	684.129683				101.81
TSFC (lb/lb/hr)	0.596				23.49
FC/seat (kg/hr/seat)	16.87				27 37
Noise (EPNdB)	79.5				16.58
Clmax TO@MTOW	2.375				14.73
Clmax LAND@MLW	2.946				7.91
T/W	0.31				11.87
Hold volume/Pax [m³]	0.173				-8.95

Table 12

Results from the VOM application for the reference aircraft

		B737-200		B737-800		ERJ-145		A320	
		Total VP	1,000	Total VP	1,695	Total VP	1,276	Total VP	1,546
				69,5%	INCREASE IN VALUE	27,6%	INCREASE IN VALUE	54,6%	INCREASE IN VALUE
30%	**The cost related to the aircraft**	Assigned value	0,300 VP	Assigned value	0,912 VP	Assigned value	0,425 VP	Assigned value	0,751 VP
9,3%	Depreciation on support buildings/equipment	1	0,093	4,413	0,410	2,382	0,222	5,999	0,558
11,1%	Ticket/Sales	1	0,111	1,000	0,111	1,000	0,111	1,000	0,111
6,5%	Administration/other	1	0,065	7,045	0,458	1,826	0,119	4,291	0,279
3,4%	Staff	1	0,034	4,858	0,165	1,407	0,048	3,419	0,116
9,3%	Maintenance	1	0,093	6,753	0,628	0,824	0,077	1,948	0,181
16,0%	Fuel	1	0,160	1,366	0,218	0,936	0,150	1,274	0,204
11,8%	Crew	1	0,118	4,858	0,573	1,407	0,166	3,419	0,403
7,2%	Interest	1	0,072	0,741	0,053	3,304	0,238	1,103	0,079
0,8%	Insurance	1	0,008	0,741	0,006	3,304	0,026	1,103	0,009
6,9%	Depreciation on the aircraft	1	0,069	4,413	0,305	2,382	0,164	5,999	0,414
6,0%	Airport (ground handling/landing fees)	1	0,060	0,405	0,024	0,146	0,009	0,965	0,058
4,4%	Navigation (en-route)	1	0,044	0,365	0,016	0,329	0,014	0,424	0,019
7,3%	Passenger services	1	0,073	1,000	0,073	1,000	0,073	1,000	0,073
15%	**The aircraft utilisation**	Assigned value	0,150 VP	Assigned value	0,180 VP	Assigned value	0,213 VP	Assigned value	0,195 VP
20,0%	Flights per day	1	0,200	1,000	0,200	1,000	0,200	1,000	0,200
20,0%	Block hours per aircraft	1	0,200	1,482	0,296	1,314	0,263	1,700	0,340
20,0%	Stage length	1	0,200	1,929	0,386	1,752	0,350	2,018	0,404
40,0%	Turnaround time	1	0,400	0,800	0,320	1,514	0,606	0,887	0,355
15%	**The maintainability of the aircraft**	Assigned value	0,150 VP	Assigned value	0,150 VP	Assigned value	0,150 VP	Assigned value	0,150 VP
13,6%	R&D	1	0,136	1,000	0,136	1,000	0,136	1,000	0,136
54,5%	Production (tools needed)	1	0,545	1,000	0,545	1,000	0,545	1,000	0,545
15,9%	Ground equipment + initial spares	1	0,159	1,000	0,159	1,000	0,159	1,000	0,159
11,4%	Special construction	1	0,114	1,000	0,114	1,000	0,114	1,000	0,114
4,6%	Disposal	1	0,046	1,000	0,046	1,000	0,046	1,000	0,046
30%	**The sustainability of the design**	Assigned value	0,300 VP	Assigned value	0,366 VP	Assigned value	0,313 VP	Assigned value	0,359 VP
10,0%	Recycle	1	0,100	0,900	0,090	0,900	0,090	0,900	0,090
10,0%	Pollution during production	1	0,100	1,000	0,100	1,000	0,100	1,000	0,100
0,1%	Taxiing	1	0,001	1,366	0,001	0,936	0,001	1,274	0,001
0,5%	Take-off	1	0,005	1,428	0,007	0,955	0,005	1,421	0,007
17,3%	Cruise	1	0,173	1,372	0,237	1,091	0,189	1,392	0,241
0,6%	Landing	1	0,006	1,450	0,009	0,973	0,006	1,353	0,008
21,7%	CO2	1	0,217	1,366	0,296	0,936	0,203	1,274	0,276
8,6%	H2O	1	0,086	1,366	0,117	0,936	0,081	1,274	0,110
0,2%	CO	1	0,002	1,366	0,003	0,936	0,002	1,274	0,003
0,1%	UHC	1	0,001	1,366	0,001	0,936	0,001	1,274	0,001
0,0%	Soot	1	0,000	1,366	0,000	0,936	0,000	1,274	0,000
0,1%	NOx	1	0,001	1,366	0,001	0,936	0,001	1,274	0,001
0,0%	SOx	1	0,000	1,366	0,000	0,936	0,000	1,274	0,000
30,8%	Noise	1	0,308	1,161	0,357	1,183	0,364	1,166	0,359
10%	**The market requirements**	Assigned value	0,100 VP	Assigned value	0,086 VP	Assigned value	0,176 VP	Assigned value	0,091 VP
2,4%	Hand baggage size	1	0,024	1,316	0,032	0,968	0,023	0,911	0,022
2,4%	Hand baggage weight	1	0,024	1,000	0,024	1,000	0,024	1,000	0,024
2,4%	Baggage size	1	0,024	1,000	0,024	1,000	0,024	1,000	0,024
2,4%	Baggage weight	1	0,024	1,000	0,024	1,000	0,024	1,000	0,024
14,3%	Seat pitch	1	0,143	1,000	0,143	1,000	0,143	1,000	0,143
1,0%	On board entertainment	1	0,010	1,000	0,010	1,000	0,010	1,000	0,010
2,4%	Catering	1	0,024	1,000	0,024	1,000	0,024	1,000	0,024
2,4%	Shopping	1	0,024	1,000	0,024	1,000	0,024	1,000	0,024
20,4%	Boarding options	1	0,204	1,000	0,204	1,000	0,204	1,000	0,204
47,5%	Boarding/Check-in time	1	0,475	0,688	0,327	2,600	1,235	0,813	0,386
2,4%	Seat reservation	1	0,024	1,000	0,024	1,000	0,024	1,000	0,024

5.1.2. Aircraft utilization

Typical aircraft characteristics were used to determine the aircraft and due to the higher stage-length of the 800 series its utilization was higher at 9.59 hours/day versus 6.47 hours a day for the 200. The 200 variant has an average stage-length of 229 nautical miles while the 800 variant is 654 nm [29]. The boarding and de-boarding time of the B737–800 takes 55% of the total turn-around time of the aircraft [30], whereas the smaller capacity of the 200 series (130 pax @ 29inch versus 189 pax @ 29inch) can decrease the overall turnaround time by approximately 25 percent.

5.1.3. Aircraft sustainability

The future use of composite materials or newly conceived materials may have a significant impact on the recyclability of the aircraft, while diminishing pollution during the life of the aircraft through lower weight and fuel burn is critical in the life cycle analysis. Relative to Thrust Specific Fuel Consumption

(TSFC), the lower the TSFC, the lower the fuel consumption per unit weight and the higher the efficiency. The Pratt and Whitney engine of the 200 series has a TSFC of 0.779 kgh/N while the CFM engine of the 800 series has a TSFC of 0.56 kgh/N [31]. Adjusteding for the aircraft cruising thrust, i.e. 19.00kN thrust for the 200 series versus 24.39kN for the 800 series, the fuel consumption per passenger for the 200 and 800 twin engine series equal 23.85 kg/h and 14.73 kg/h respectively. Similarly, the efficiency during take-off, landing and cruise conditions are mainly governed by Specific Fuel Consumption (SFC), while the thrust-to-weight ratio is another important factor during cruise as it relates to the inverse of the lift-to-drag ratio (or the efficiency of generating lift). The 800 series had in all four cases better values for take-off, landing, cruise and thrust-to-weight ratio of 0.779; 2.070; 2.730; 0.277 respectively versus 0.56; 2.200; 2.960; 0.279 respectively. Other chemical compounds produced during combustion, such as NO_x, SO_x, soot etc; were also compared with respect to the SFC of the aircraft models, with the next generation coming out significantly better as seen in Table 12.

The noise levels associated with the next generation engines and airframes are also much lower than those of first generation aircraft. The 800 series is rated 80EPNdB [32] while the B737-200 is rated 95.3EPNdB [33], which is considerably lower for the next generation version remembering that this is a logarithmic noise metric.

5.1.4. Market requirements

The seat pitch for both airliners was set to ‘high density’ capacity, i.e. 29 inches, while inboard entertainment was not provided for the low fares airline. Both aircraft have two doors available for boarding, i.e. one in the front of the cabin and the other in the back), while catering, shopping and seat reservations were assumed to be operated in the same way for either aircraft. However, due to the larger capacity of the B737-800, boarding times were increased for the same flow of passengers. Finally, the 800-series was also accredited more cargo volume allocation per passenger (than the 200 series: 0.25 m^3 verses 0.19 m^3 respectively.

5.2. Comparison with other competing aircraft (737-200/ERJ-145/A320)

Following the comparison of the two aircraft from the previous section, this section expands the analysis and the validation of the value model with the addition of two different aircraft from the same range of aircraft. The challenge was to find two airlines operating a large, preferably single type fleet, so that the performance comparison was as relative as possible to the Boeing 737-200 operated by Ryanair. The best solution for this also in terms of available date was the Embraer ERJ-145 operated by ExpressJet [34] and the Airbus A320 operated by EasyJet [35].

5.2.1. The Embraer ERJ-145 analysis

ExpressJet is one of the world’s largest regional airlines, providing both commercial service and corporate flights. In 2008 it operated a fleet of 244 Embraer ERJ-145 aircraft, which included both the ERJ-145 and ERJ-145 XR types, and offered 20287.39 million Available Seat Kilometres (ASK’s) according to their 2008 Annual Paper [36].

5.2.1.1. Cost related to the ERJ-145. The 2008 Annual Paper also provided the necessary data for the cost related to the Embraer ERJ-145(XR) aircraft. The costs, published in 2008 dollars, were first corrected for inflation [37] and then converted to Euros based on the currency exchange rate at December 31st 2009 [38]. Because the regional jets are leased instead of being owned by ExpressJet, the depreciation does not include the full depreciation of the aircraft fleet. Therefore the *aircraft cost* used in the Value Model is defined as the sum of depreciation and renting each particular aircraft. As with the Boeing 737's, the purchase price [39] of the Embraer aircraft forms the basis for the interest and insurance costs and all of the operating cost factors are then expressed in Euros per ASK and compared to the baseline Boeing 737-200. With respect to the 737-200, the ERJ-145 scores more value points in the section related to the cost of the aircraft.

5.2.1.2. Aircraft utilization of the ERJ-145. The ERJ-145 provides a capacity of 50 passenger seats and a maximum range 1550 nm [40], which is significantly lower than the Boeing 737's. The lower capacity on the other hand reduces the time required for boarding and thus the turnaround time, when using the same assumptions earlier made for the 737's. The average utilization is 8.5 hours per day, with an average stage length of 594 miles [36]. The advantage of shorter turnaround time is clearly expressed in the high value points for aircraft utilization.

5.2.1.3. Sustainability of the ERJ-145. The two Rolls-Royce AE 3007A1 E engines utilized on the ERJ have a quoted noise level of 77.9 EPNdB [41] and a specific fuel consumption of 0.63 lb/lb/hr [42]. The thrust at cruise altitude was required in order to calculate the fuel consumption during cruise. Consequently, as for the analysis carried out for the 737s: assuming that atmospheric conditions at cruise altitude h and sea level sl are given by the International Standard Atmosphere and that the thrust T is proportional to the mass flow of the engine given by $\dot{m} = (\rho A c)_e$; with the engine's cross sectional area A_e and flow velocity c_e constant, thrust is proportional to the air density ρ so that by using the ideal gas law $\rho = p/Rt$, it can be calculated that the thrust can be scaled according to altitude$h$ with respect to sea level as follows:

$$\frac{T_h}{T_{sl}} = \frac{p_h t_{sl}}{p_{sl} t_h} \tag{15}$$

Assuming sea level conditions of $p_{sl} = 101325 Pa$, $t_{sl} = 288.15 K$ $T_{sl} = 7040 lbs$ [43] and cruise conditions at $h = 35000 ft$ of $p_h = 23841.8 Pa$, $t_h = 219.05 K$, Eq. 14 yielded a thrust at cruise conditions T_h of 2179.1lbs or 9.692 kN: yielding a fuel consumption of 37.54 kg/hr/seat. Due to the lower seat capacity, this fuel consumption per seat was then higher than that of the 737's. Consequently, although the ERJ-145 is quieter than both the 737's, the ERJ-145 then received lower Value points for sustainability due to the higher weighting factor of fuel consumption per seat in the value model.

5.2.1.4. Market requirements of the ERJ-145. Although the ERJ-145's cargo hold volume [44] per passenger is lower than the 737's, the boarding and check-in time is much shorter due to the lower capacity. Therefore, since the boarding and check-in time had a high weighting factor in the model, the ERJ-145 scored better than both 737 on this particular aspect.

5.2.2. The airbus A320

EasyJet, as Ryanair's biggest competitor in the European Low Cost Carrier market segment, operates a large fleet of 181 aircraft which includes 164 Airbus A320 family aircraft and also 17 Boeing 737-700 [45]. It is well known that EasyJet was able to negotiate a very low acquisition price for the Airbus aircraft due to market conditions, which is a factor that can substantially distort the normal value analysis. Notwithstanding, the VOM approach is equally relevant but then the analysis is very specific to that one customer and the acquisition (and service) deal that they were able to negotiate, i.e. which may be then different for anther airline operating the same aircraft. Within the next few years, it is anticipated that the 737-700s will be either be sold or removed from service and replaced by Airbus A320 family aircraft. For this analysis however it was assumed that EasyJet's financial and utilization data is representative for the Airbus A320 family and that the influence of the 17 Boeing 737-700's on this data can be neglected.

5.2.2.1. Cost related to the A320 family. The operating cost for the A320 family are based on EasyJet's 2009 annual report [45] with the figures being converted from pounds sterling to euros based on the currency exchange rate at September 30th 2009 [46], at EasyJet's financial year-end. The costs were then expressed in Euro per ASK and compared to the baseline Boeing 737–200 from Section 5.2. The purchase price which is used in this analysis is the average sales prices in 2008 for the A319 [47] so the analysis does not incorporate EasyJet's lower negotiate acquisition price as those figures are not available. Similar to the situation of ExpressJet, EasyJet does not own all of its aircraft, so the *aircraft cost* input accounts for depreciation relative to aircraft rather than fleet in the value model. Relative to its competitor, the 737-800, the A320 does not score as well in terms of cost in the value model due to the higher Direct Operating Costs of crew, maintenance and administration while, the A320 scores significantly better when compared to the older 737-200.

5.2.2.2. Aircraft utilization of the A320 family. EasyJet's aircraft have a weighted average capacity of 160 passengers based on their fleet composition [48] and maximum range of 3700 nm [49]. In 2008–2009 EasyJet achieved an average utilization of 11 hours and an average stage length of 684 miles [45]. Due to the high utilization figures, the EasyJet's A320 scores slightly higher than Ryanair's 737-800.

5.2.2.3. Sustainability of the A320 family. The two CFM56-5 engines have a noise level of 79.5 EPNdB [41], which is similar to that of the 737-800. Its specific fuel consumption of 0.596 lb/lb/hr [50], which together with a thrust at cruise conditions of 22.2kN50, yields a fuel consumption of 16.87 kg/hr/seat. Because this is slightly more than the 737-800, it scored less value points in the value model for sustainability.

5.2.2.4. Market requirements of the A320 family. The A320 family features the smallest cargo hold volume [51] of all aircraft in this analysis. However the lower passenger capacity theoretically yields a lower boarding and check-in time, although figures are nt available to back this assumption up. The A320 therefore score slightly higher than the 737–800, but still lower than the 737-200.

6. Discussion

Through the VOM analysis and validation studies presented the Boeing 737-800, Embraer ERJ-145 and Airbus A320 have been compared with respect to the baseline Boeing 737-200. In summary according to Table 12, the Embraer resulted in 27.6% increase in value, the Airbus A320 in a 54.6% and the Boeing 737-800 in 69.5% over the older baseline aircraft. This Section expands on these results and some of the wider issues in terms of the validation of the VOM approach.

6.1. The VOM value model

The inputs for the value model as implemented here-in were[1] linear and also linearity was assumed between the parameters, e.g. where the insurance and interest costs were related to the purchase price. In reality of course linearity is a large assumption and there will be many conflicting external factors will also influence the characteristic of the relationships and interdependencies between the parameters and variables. In terms of interdependency, for example, the turnaround time is also dependant on the boarding time, which is linearly dependent on the amount of passengers to be boarded. However, the current implementation of VOM assuming the linearity is deemed to be reasonable for such a broad modelling problem where the nature of the study is by definition indicative and subjective. The aim is not to calculate a specific absolute magnitude of value but more to guide decision making in an effective and holistic manner. Consequently, the effect of linearity on gradient and the partial differentials of value is the more pertinent question. Certainly, assuming linearity for smaller changes in input variables is a well accepted approach within optimisation while the potential for inaccuracy becomes larger as the increments increase. Therefore, one is looking for significant differences in value between design options to be more certain of the preference for one alternative over another while also sensitivity and scenarios studies would be important to make the analysis more robust.

Other important specific assumptions included that within the model no differences in depreciation on property and flight equipment were considered, as details of the cost structure were unknown. Also, in comparing the four aircraft, no specific flight envelop was set and each aircraft was compared with respect to its mission set by the respective airline. The Direct and Indirect Operating Costs were not only aircraft dependent but also differences in the business models and operating plans of the Carriers may have resulted in fluctuations in the costs relating to the various aircraft; without also taking into account local regulations, etc. However, given the implementation of sustainability, utilization and market requirements, the VOM model not only indicates value changes from a technical perspective, but also takes the increase in business value and other wider constraints into account. Efficient operations and economies of scale also play an important role in this model, and the intention to include safety is a future specific goal.

6.2. The AHP VOM implementation

The main contribution of AHP is the pair-wise comparison for each trade criterion and design option so that the VOM Value can be executed in a quantitative manner. Alternatively, a more deterministic mathematical expansion could be implemented for the value model, if the data and information is available to support this level of detailed modelling, or the AHP solution could be developed to use more complex non-linear functions. However, in the first instance the presented research is limited by the scope and to a large extent by the accuracy and high level nature of this analytical approach. Consequently, AHP has been implemented as suggested in a linear manner which seems simplified although the authors propose that this is an acceptable characterisation of such a subjective relationship involving value; although the limitations of AHP due to the use of linear relations in the figure of merit function are well pointed out by Collopy [52]. This limitation has the consequence that the AHP can be better used in a trade-off with existing components that by themselves are suitable for the task they are selected for and understood in terms of range, rather than assuming linearity as an acceptable approximation for relationships that have never been characterised.

[1] noise reduction is measured on a logarithmic scale but was used herein in a linear fashion with respect to the comparative study.

6.3. 737-200 vs. 737-800

The results of the value model analysis between the Boeing 737–200 and 737–800 showed a significant value increase for the next generation aircraft. As these aircraft were operated by the same airline, one may state that the validity of the value model between these aircraft is highest and forms the most credible evidence of validity and usefulness of VOM approach, or put another way one assumes the absolute accuracy to have been highest here. The aircraft value improvement is primarily due to the technological advancements that were carried out for the more modern variant, including: SFC, weight/pax, noise, higher utilisation rate, lower maintenance costs, lower depreciation of the aircraft results in higher business value, etc.

6.4. 737-800 vs. A320

Indicatively, it seems that the outcome of the proposed VOM methodology is quite realistic since the gap between the Boeing 737-800 and Airbus A320 was relatively small. It was evident that the most important difference between the B737-800 and A320 was the cost of maintenance between the aircraft. However, since Ryanair has a very recent fleet, the maintenance costs between both carriers (Ryanair and EasyJet) are very difficult to compare in terms of life cycle costing and performance. The '*U.S. Department of Transportation: form 41*' claims that the Boeing 737 maintenance cost are up to 35% lower than the A320 [53] and when this smaller change was artificially applied in the model, the A320 yielded a better 61.4% value increase which is still lower but approaching that of the 737-800's.

6.5. Embraer ERJ-145

The results for the Embraer ERJ-145 showed that it yields a high utilization value, due to short turnaround, boarding and check-in times. The performance per ASK were, however, much lower than when compared to the other aircraft because of its lower seat capacity and average stage length. Overall, the ERJ-145 was shown to be less valuable when compared to the 737–800 and A320, although again this is not a mission specific analysis as stated in Section 6.1.

7. Reflection

In reflection, it has been established that the VOM approach has considerably developed the original concept of Value Engineering from the initial attempts of Miles and later colleagues [54] to couple cost [55] into the basic engineering analysis process through value. VOM is closely related to the VDD [1] approach but is distinct in putting the emphasis on operationally realised value as the basis of the Value Function or Model while also specifically advocating the use of value differentials or gradients rather than an absolute statement of value. The use of AHP has been adopted in order to quantitatively manipulate the Value Model and Function but limitations of this approach and he assumptions of linearity have been emphasised. Notwithstanding, the authors believe the AHP has been usefully adopted to implement VOM in the current work, especially given the difficulty in generating a full deterministic model of the whole value system with each component at the same level of fidelity, etc. Once again the authors highlight the fundamental principle that value analysis is inherently subjective and time based and therefore a more flexible approach should be adopted when adapting it to engineering analysis. Ultimately, engineering value analysis is indicative, and should be rigorously tested for sensitivity and robustness, preferably also linked to certain scenarios that create useful and meaningful points of reference for he design to more clearly see and understand the emergent impact of design decisions on the operational value of the products and entered into service.

Certain specific observations have been made in Sections 6.3 and 6.4. It has already been highlighted that these results are not mission specific and therefore are more indicative of the general potential. It can be noted that in general we may conclude that next generation aircraft in general are improving in terms of their overall value proposition but that the aircraft need to be well tailored to their specific mission. This was evident for the Embraer, which was at a disadvantage relative to seat capacity and range in the current general study; whereas for routes with slightly lower passenger demand it would have the optimal load factor and therefore have a much higher value rating. However, in general, apart from the matching of aircraft and mission, the impact of costs has been highly evident and other issues such as maintenance, utilisation and SFC. The use of Sustainability in the analysis is a very subjective element where a policy maker using the methodology would rate it much higher than an operator and perhaps the most interesting aspect is the ability to play about with changing its impact and also seeing which decisions are either less or more critical. Again, a key aspect here is that the VOM approach can give the designer and decision maker more understanding of the impact of certain decisions and even quantitatively assess these to offer an indicative sensitivity rating, which albeit should be itself tested for sensitivity and robustness.

8. Conclusion

After the application to four aircraft and taking into consideration the assumptions and limitations of this model, the Value Operations Methodology was shown to yield a realistic and meaning full output that supports and extends the Value Driven Design (VDD) philosophy. The comparison of the older Boeing 737-200 with the next generation Boeing 737-800 shows large improvements even when evaluated under the more holistic value analysis approach, especially from technical, operational and economical perspectives. The comparison with the Embraer ERJ-145 showed that while the utilization value is very high, its performance per ASK was rather low, leading to a lower value rating than when compared to the larger aircraft. Finally, the comparison between the Boeing 737-800 and the Airbus A320 showed that there was a considerable difference in the maintenance cost, while on the other value aspects utilised these two aircraft were strong competitors. However, in order to increase the validity of the model, it is recommended that future evaluation and extension of this initial work should be carried out by comparing the aircraft within a specified flight envelop. In addition, the implementation of the VOM approach herein assumed the value model to be made up of relationships of a linear type whereas parameters may well have a non linear nature. The ability to model these more complex relationships should be explored along with the usefulness of doing so or put another way, limiting the useful range within which the linear assumptions remain valid and useful. For example, a refined version of VOM implementation presented herein may be to first calculate a value baseline point and then to assume linearity in moving incrementally from this point using an optimisation search based on the value gradients, after which a new value point can be recalculated in more detail before again moving away again from this new point through the incremental optimisation search. Consequently, the linearity assumption could be used to facilitate the efficient optimisation search while the repetitive updating of the value calculation or recalibration helps ensure a more accurate value analysis. As stated in the paper, the VOM approach is generic in nature and may be adopted or implemented in many different ways when actually manipulating the value function in the model.

The most fundamental conclusion from the work presented is actually that the VDD and VOM approaches simply promote the sustained application of the main utility values that are always originally recognised and understood by the expert engineers in these world-class OEMS but which, due to the complexity of the product and enterprise, tends to be disaggregated into isolated requirements that results in a loss of control on managing their desired systemic input, control and outcome. Ultimately, this leads to optimisation at a sub-system level and that is especially unacceptable for a complex system (with many sub-systems and even acting within a recognised System of Systems), whereas the extended re-focus of VOM within VDD helps to significantly shift the design effort back to creatively solving the main goal of realised operational value, rather than simply and somewhat robotically making sure the isolated requirements are satisfied. The key message of the paper is the need for value modelling within engineering, where value is realised through operational excellence.

The concept of integrating value analysis into the product/service development process is fundamental to every CEO and the best engineers but it has never been well formalized in an analytical, integrated and widely accepted manner. That commercial stakeholder position is based on a financial and competitive basis whereas this paper has considered an even wider value scope including sustainability etc. It is suggested that this VOM implementation at an early concept design stage (along with the more detailed engineering design analysis tools) could open up a significantly new approach to aircraft design methodology that may well help us sustain air transport beyond many of its current financial and environmental challenges, to deal more proactively rather than reactively on real and pressing holistic design drivers!

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