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A Value Operations Methodology for Value Driven Design: Medium Range Passenger Airliner Validation

R Curran[1], T. Abu-Kias[2], M.J.F Repco[2], Y.L.J. Sprengers[2], P.N.C.S van der Zwet[2] and W. Beelearts[3]

Air Transport and Operations (ATO)
Faculty of Aerospace Engineering
The Technical University of Delft (TUD)
Kluverweg 1, 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 may well still be economically driven but incorporating drivers of a much more holistic cause: proactively rather than reactively!

1 Introduction

The paper is primarily about the development 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 aircraft with respect to each other. Section 2 shows the creation of the Value Model that is used in the design process; Section 3 then shows how this Value Model is used in the Analytic Hierarchy Process for the final design process. Section 4 contains the validation part of the ValueModel where input variables of a Boeing 737-200, Boeing 737-800, Embraer ERJ-145 and Airbus A320 are used. Section 5 contains the discussion of the results, while the Conclusions and Recommendations are drawn in Section 6.

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[1] Chair of Air Transport and Operations and Section Head, Senior Member of AIAA
[2] Masters Student, Air Transport and Operations Section
[3] Research Assistant, Air Transport and Operations Section

2 Value Model Development

In Value Driven Design (VDD), not only the value of today's basic and primitive economic drivers needs to be considered, but also the value for the customer and the value to society, which will ultimately result in an economic impact not currently accounted for. In order to be able to quantify the amount of value of different design options and the total design, a model is proposed that captures the value of an aircraft design and its operational realisation in terms of value-added. Quantifying these true ultimate goals in an early design stage 'demystifies' so called hidden goals and is therefore significant in the decision making process if not of a paradigm shifting nature. The following Section will discuss how a conceptual model was set up and which input parameters were identified, while the latter part considers the associated value weightings or value coefficients.

2.1 Methodology

Ralph L. Keeney (1992) raised 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 is based on the idea that a cost differential between two systems consisting of a set of similar characteristics can be used to value the characteristics. The hedonic model is explicitly based on a price constant, α. A typical hedonic function that connects the variation in cost to the variation in characteristics is shown in Equation 1.

$$\ln(P_1) = \alpha_1 + \sum_{j=1}^{m} \beta_j x_{ij} + \varepsilon_i \qquad (1)$$

where most importantly j=1..m is a set of value levers of the system that is analyzed, P is the price, β is the weight factor. It is used to define the percentage change in price the stakeholder is willing to pay for an adjustment in the value lever x. The value model is based on Keeney's representation of theorems for quantifying values using utility functions. The theorem of Fishburn (1965), suits our purpose best. Keeney defines Fishburn's function as the additive utility function, see Equation 2:

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

Were u_i is a single attribute utility function over attributes x_i and k_i are the scaling constants needed for value tradeoffs. Characterizing a decision problem and basis for a value model is a set of goals G_i, $i= 1,\ldots.,N$. The consequences x are part of the attribute X measuring the goal G. If the additive utility function only exists when the attributes are additive independent to each consequence x there exists a corresponding number u indicating the value[2]. The proof of the additional utility function is given in Fishburn 1965[3].

It is concluded that the hedonic model establishes: a) the differential principle: that it is much more reasonable to relate the value of one instance with another (rather than trying to measure absolute value); and b) the additive principle: that value relating to an instance should be simply accumulated (rather than trying to actually model each individual subjective element. Therefore, the authors propose incorporating the following value levers in a differential-additive valuation manner as shown in Equation 3; including: Costing C (revenue/cost), Utilization U, Maintainability M, Environmental Quality E, Passenger Satisfaction P with their corresponding weighing factors. 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 current 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.

$$\Delta V = \alpha_C(C_1/C_0) + \alpha_U(U_1/U_0) + \alpha_M(M_1/M_0) + \alpha_E(E_1/E_0) + \alpha_P(P_1/P_0) + (\alpha_S(S_1/S_0) + \varepsilon) \qquad (3)$$

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 characteristics and the characteristics of the corresponding aircraft under consideration. The *Costing* value lever is worked out in detail as shown in Equation 4.

$$C = \omega_1 \cdot d[\text{DepreciationIOC}] + \omega_2 \cdot d[\text{Ticket/sales}] + \omega_3 \cdot d[\text{Admin/other}] + \omega_4 \cdot d[\text{Staff}] + \omega_5 \cdot d[\text{Maintenance}] + \omega_6 \cdot d[\text{Fuel}] + \omega_7 \cdot d[\text{Crew}] + \omega_8 \cdot d[\text{Interest}] + \omega_9 \cdot d[\text{Insurance}] + \omega_{10} \cdot d[\text{DepreciationDOC}] + \omega_{11} \cdot d[\text{Airport}] + \omega_{12} \cdot [\text{Navigation}] + \omega_{13} \cdot d[\text{PaxServices}] \quad (4)$$

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, $\omega_{1\text{-}13}$, in Equation 4 indicate 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 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 Equation 4 and the cost influence model. 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 needed, directly influences the cost variable C, see Equation 4 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, see Equation 4 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.

2.2 Value Model percentages

The next section describes how the weighting factors of each value model item are obtained for the application to the design of an airliner.

2.2.1 The Model

The presented model is based on 5 main pillars of value: Cost, Sustainability, the Market, Utilization and Maintainability (where Safety is currently left out to reduce complexity). The design requirements[5] of the airliner suggest that it is important that the sustainability targets are reached and also the economics of the design should be optimized from a value perspective. Since most value for the airline is generated by keeping the costs as low as possible but even more importantly ensuring the revenue to be as high as possible, it is important that the aircraft is operational as often as possible with as little cost as possible. A reduction in cost for the airline will also enable the airline to offer a lower ticket price and this will thus also be beneficial for the passengers. The market needs are determined by the passenger and they only add value for the passenger in the current methodology. This 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. Based on this analysis the total value will be obtained through the division presented in Table 1. This is intentionally set to be challenging to current short term financial thinking which would automatically put cost at say 60-80%. However, the hypothetical approach stipulated in Table 1 underlies the fundamental shift in driving the design process with an operational value analysis assessment that is better positioned to also anticipate future economic constraints through a more holistic approach. Surely, this is fundamental to the sustained trajectory of aerospace innovation and its positive and seminal mpact.

Table 1: Airliner design Value Model – The division of total value

Value in Airliner Design	
Cost	30%
Sustainability	30%
Market	10%
Utilization	15%
Maintainability	15%

2.2.2 Costing

Indirect Operating Costs (IOC) relate to costs for the airline that are not affected by using the airliner, while Direct Operating Costs (DOC) relate directly to using the airliner. A study into general airliner cost models of Boeing[6], ICAO[7], Martinair model[8],Boeing/MIT[9] and another MIT[10] model resulted in the 13 items in Table 2.

Table 2: Determining the weight factors in 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%

With these percentages, value is gained by looking at how much percent a certain item of the airliner will contribute to the reduction of these costs. Note that in this case it does not relate to how much money is saved in absolute terms.

2.2.3 Aircraft Utilization

Crucial to an operations-oriented value methodology, the items that are important to aircraft utilization are determined by how much time the aircraft is used to generate revenue. According to Doganis[11] short haul fights generate more profit than long haul flights, based on this it is determined that the stage length should be relatively small. Flights per day and block hours per aircraft should be as high as possible and the turnaround time should be as low as possible. 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. Based on this judgement the weights are as presented in Table 3.

Table 3: Determining the weight factors in the utilization value lever

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

2.2.4 Maintainability

Maintainability relates to all aspects of an airliner that relate to the production and the maintenance of the airliner. Research into the life cycle cost of an airliner[2] showed 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 considered in the calculation of the maintainability (lever) component; as it is the cost lever that incorporates this aspect. When the remaining five aspects are scaled so that they contribute 100%, this results in the percentages as presented in

Table 4.

Table 4: Determining the weight factors in 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%

2.2.5 Environmental Quality

The environmental quality can be listed into three categories: Flight Procedures, Aircraft and Engine Design, and Production. The Production is determined to be of 20% importance in the total model, which leaves 80% for the other two. The subdivision of the Flight Procedures and Aircraft and Engine Design part is done according to the distribution by 'Vital' [12]. They claim that an improvement of the ATC procedures and an improvement of aircraft and engine design can lead to a fuel consumption reduction of 12%, 20% and 20% respectively, which gives a total reduction of 52%. Therefore the Flight Procedures (12%) and Aircraft and Engine Design (40%) are given a weight factor according to that difference. With the overall parts weighted, it is time to further subdivide the three parts of the value of sustainability. The impact of optimizing the flight procedures (Taxiing, Take-off, Cruise and Landing) is determined by how much fuel is burned during those stages. An analysis using data from Ruijgrok[13], H. Nojoumi, I. Dincer, G.F. Naterer[14], smartcockpit[15] and RITA[16] that related engine thrust settings to time yields the division of the particular items. The Aircraft and Engine Design items division is based on the requirements on noise reduction and pollution reduction. Because of this, noise and pollution are determined to be evenly important. The further subdivision of the pollutants is based on the emission index (EI) of the different pollutants[13] which indicates the amount of pollutant produced for every kg of fuel burned. Some of these indexes depend on the thrust setting and for those items the value for the time weighted average thrust setting during fight is 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 particular pollutants. The division of the importance of the items in the production phase is determined to be evenly divided. This is justified as both a reduction in pollution during production and a better recyclability have a great impact to the sustainability of the design. These analyses resulted in the weighting factors as stated in

Table 5.

Table 5: Determining the weight factors in the environmental quality value lever

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%

2.2.6 Passenger Satisfaction

The evaluation of the Passenger Satisfaction is based on the Contingent Valuation method, which features a market survey that determines how people value certain aspects. A market survey was carried out among a limited number of participants within the University that provided the input of the market requirements part of the value model, as is presented in Table 6. The weighing factors are also based on the market need survey. From this survey, it can be concluded that passengers prefer speed (19%) over onboard service (5%) and the comfort of the aircraft (4%). First these percentages are scaled to form a total of 100% and then each item is further subdivided. The onboard services are further subdivided into services and entertainment and from the survey it can be concluded that passengers rate the services (5% Not Important) as more important than the entertainment (28% Not Important). The survey does not provide a preference of the passenger for a certain type of check-in but based on these findings the weighting factors are assigned accordingly.

Speed is determined by how the boarding is carried out and the time required for the whole procedure of boarding and check-in, which is also influential on the turnaround time. Consequently, the Boarding ption is considered to have a smaller impact on the speed (30%) than the Boarding/Check-in time (70%). In the Service Section most services are judged to be evenly important, while the entertainment is judged to be of less importance and comfort is 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 that service should be considered as a total package that needs to include all items related to service and cannot be easily disaggregated.

Table 6: Determining the weight factors in 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%

3 Identification of Value Components through Analytic Hierarchy Process

3.1 Generic Methodology

The trade-off is organized using the Analytic Hierarchy Process (AHP) from the NASA Systems Engineering Handbook[17]. This technique is developed by Thomas L. Saaty and it produces a figure of merit for each design option. The NASA handbook describes the process as follows:

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.*

By using the above approach from the AHP it is possible to determine the best design options in a trade-off based on several trade criteria with unequal weight and also for non-quantifiable criteria.
The first step is to select the trade criteria for the trade-off and possibly to expand each criterion to several items. After the criteria are selected the next step is to establish the relative importance of each trade criterion over the others. This is done by making pair-wise comparisons between the different criteria. In each comparison it is determined how much more (or less) important one criterion is over the other in relation to the design that is to be traded off. The scale of the comparisons runs from 1 to 9 and the reciprocal values (1/9 to 1). When all n criteria are compared to each other the results are put in a matrix, resulting in an $n \times n$ comparison matrix (

Table 7) where, two items are of particular importance: the eigenvalue and the eigenvector. Firstly, the eigenvalues of a matrix are obtained through solving Equation 5 for λ; where A is the comparison matrix, I is the identity matrix and λ is the eigenvalue[18]. 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 [18].

$$\det(A - I\lambda) = 0 \tag{5}$$

Secondly, the eigenvector of a matrix is obtained using Equation (6) 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. [18]

$$Ax = \lambda x \overset{\Delta}{\rightarrow} (A - \lambda I)x = 0 \tag{6}$$

Regarding the comparison matrix, Saaty[18] states that if the comparisons are done perfectly 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 only one eigenvalue that is non-zero. When the normalized eigenvector belonging to that non-zero eigenvalue is obtained, the values in the eigenvector ($\overline{v} = [v_1, v_2, .., v_n]^T$) represent the weighting factor of each criterion[19].

	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	

Table 7 - Example comparison matrix

However, since the comparisons are performed by naturally subjective actors who compare items that are not necessarily easy to quantify there will almost certainly be inconsistencies in the comparisons. Saaty has shown[20] that the eigenvalue method 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. Any inconsistency in the matrix will show up in the Consistency Ratio (CR) (see Equation 7; where *CI* is the Consistency Index and *RI* is the Random Consistency Index). The value of the CI is obtained using Equation 8, in which λ_{max} is the largest eigenvalue of the n x n comparison matrix[21]. The value for *RI* is obtained from

Table 8, which shows the result for the *CI* value of a matrix of size n x n when the average value is taken from 500 computations on reciprocal (comparison) matrices with randomly chosen inputs; as is explained by Saaty[21].

$$CR = \frac{CI}{RI}, \text{ where: } CI = \frac{\lambda_{\max} - n}{n-1} \qquad (7)\ \&\ (8)$$

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

Table 8 - Random consistency Index (RI) values for reciprocal (comparison) matrices of size n x n

For the case that the comparisons relate perfectly to each other, the value of CI (and thus also CR) will be zero. This is the result of the fact that for a perfect comparison there is only one eigenvalue, which is equal to the trace of the matrix and thus λ_{max} is equal to n. For the case that there are inconsistencies, the comparison matrix will not be perfect and λ_{max} will differ from n. λ_{max} is obtained with Equation 1 and the result is a non-zero value of CR. To know if the results are still valid, Saaty states as a basic rule that the value of CR should not exceed 0.10 by very much[21]. If CR is larger than 0.10 the comparison matrix should be looked at again and should be updated.

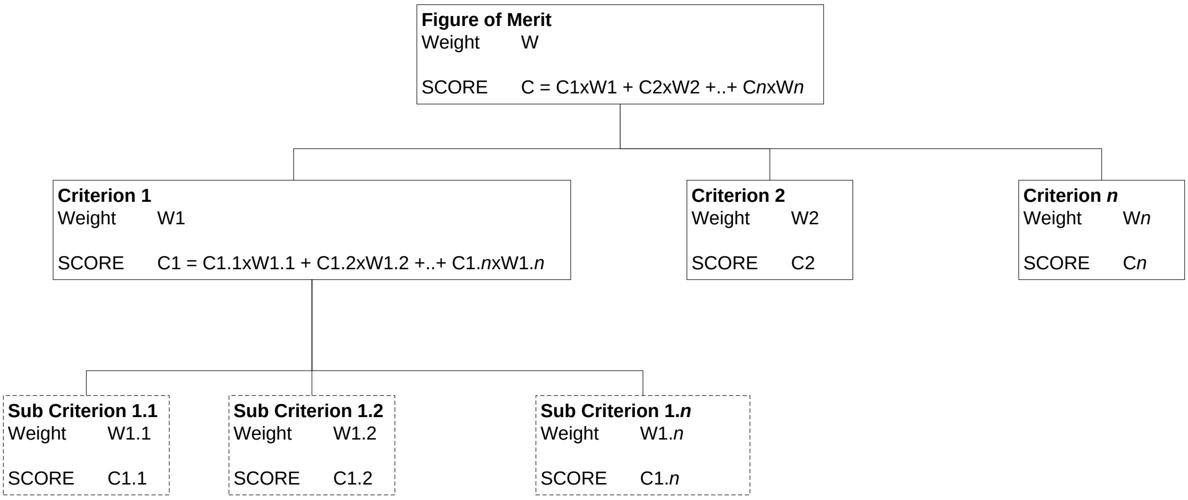

Figure 1 - Calculation of the Figure of Merit

After the weight factors for the trade criteria (and subdivision of the trade criteria) are determined, the design options are evaluated according to those criteria. Pair-wise comparisons are made between the different options for each criterion and the results of these pair-wise comparisons are then evaluated in a comparison matrix (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 Figure 1). The overall figure of merit is obtained by first multiplying the scores for each criterion with the corresponding weight factor (W1 to W*n*), which are obtained during the comparison process for the trade criteria, and then adding the results on each trade criterion for each design option. The option with the highest value is the winner of the trade-off.

It should be noted that when looking into 1 the following restrictions apply in Equations 9 and 10

$$W = W1 + W2 + .. + Wn = 1 \quad \& \quad W1 = W1.1 + W1.2 + .. + W1.n \qquad (9)\ \&\ (10)$$

By using this method the designers who already have the best knowledge of their part of the design will perform the trade-off of their particular design options. During the trade-off, the experts on the different options have the possibility to consult other experts on how to interpret the different trade criteria, which in this case probably is most applicable to the value part of the design. After each trade-off, the presentation of the results of the experts to the other group members will make sure that everyone's own interpretation of the trade criteria is tested against those of the others. This will also make sure that any personal preference to a certain option by the experts does not affect the choice of the best option.

3.2 Methodology Application

This section will describe how the method from the previous section is used in the design process of an airliner as it was performed by a 10 person, 10 week full time group of undergraduate students in the 2009 Design Synthesis Exercise at the faculty of Aerospace Engineering of TUD[22]. In this section an example will be given of the method utilized for selecting the engine type for the airliner under consideration. The trade criteria for this trade-off consist of: Regulations; Requirements; and Value. The Regulations are those that are set by the authorities and which have to be followed accordingly. The requirements are those that are identified from the requirements analysis and the value comes from the value model. In this trade-off the value model is used to indicate how each design option compares to the other regarding the inherent amount of value of the option. There is no further sub division of the trade criteria. Figure 2 provides the overview of the calculation of the figure of merit for the airliner components.

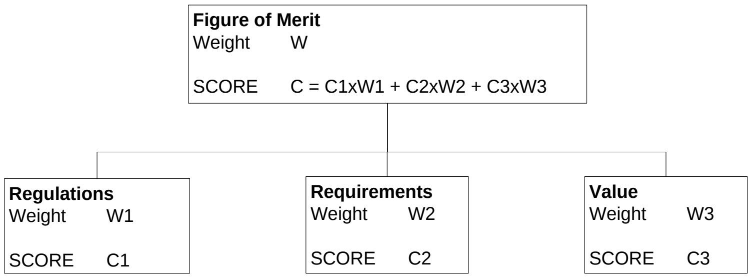

Figure 2 - Calculation of the Figure of Merit applied to airliner components

The determination of the weights of the trade criteria are done by making pair-wise comparisons between the criteria on the bases of how much more (or less) important each criterion is over the others. The results are put into a comparison matrix and the eigenvector provides the weight (W1, W2 and W3) of 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. The requirements are judged to be 5 times more important than the regulations, value 3 times more important than the regulations and requirements 3 times more important than value. This because all engines under consideration are certified by the ruling authorities and because engines are a vital component when design (performance) requirements is considered. The resulting matrix (with all reciprocal values filled in) is a 3x3 matrix. The eigenvalues are calculated with Equation 11:

$$\det(A - I\lambda) = \det \begin{vmatrix} 1-\lambda & 1/5 & 1/3 \\ 5 & 1-\lambda & 3 \\ 3 & 1/3 & 1-\lambda \end{vmatrix} = -\lambda^3 + 3\lambda^2 + \frac{16}{45} = 0 \qquad (11)$$

Which has only one real solution: $\lambda = 3.0385$**. With reference to Equation 4 this results in a Consistency Index of:**

$CI = \frac{3.0385-3}{3-1} = 0.0192$**, and consequently, with reference to Equation 3 and**

Table 8, a Consistency Ratio of: $CR = \frac{0.0192}{0.58} = 0.033$

The value of 0.033 is less than 0.10 and therefore the results from the matrix are considered valid. Using Equation 2 and solving for the non-trivial solution (in this case done by using the *"eig"* command in MATLAB) the eigenvector is obtained. Normalization of the eigenvector results in the eigenvector as provided in

Table 9. In this case the weight of regulations is considered not to be relevant, because even when it is added to the weight of value the total weight is less than halve of the weight of requirements. Because of this the regulations are not looked at in the trade-off for the engine type and its weight is added to that of requirements.

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

Table 9 - Example comparison matrix

In the calculation of the weights for the trade-off of the other components the following rationale is used. For the fuselage design the regulations and requirements are of no importance because in the more detailed design all regulations and requirements can be adhered to for every design. Therefore the only point of importance is the amount of value that can be added with every design. Also in the wing design it is possible to design in such a way that the wing adheres to all regulations and requirements and therefore also in this design the opportunity to add value is considered the only criteria of importance.

The selection of which material to use for different parts of the aircraft is only based on the possibility to add value because the regulations and requirements do not apply to the material. Regulations are important in the certification of the materials, but once the materials are certified for the use in an aircraft this aspect is no longer a decisive aspect. In the trade-off of the braking systems the only criteria is the opportunity to add value, regulations and requirements are not important because the requirement of value already is incorporated in the value model and the regulations are not important because they don't apply to how the braking is done. The requirements don't apply to the choice of which power system for ground operations to choose, the regulations do apply since the current APU will probably be banned in the near future. Also the opportunity to add value is important. The taxiing system is fully determined by the opportunity to add value. Regulations and requirements don't apply, only for the sustainability requirements but all option should be able to reduce the impact on the environment. In the trade-off for the location of the fuel tanks the regulations are of no importance since every possible location is already used and therefore determined to be within the regulations. The requirements don't apply to the location and therefore only the possibility to add value is considered. When the same procedure is followed as for the engine type, this results in the weight factors provided in

Table 10:

	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

Table 10 - Weight factors of each trade criteria for each airliner component[5]

Model	Boeing 737-200 (1999)			
Carrier	Ryanair			
Fleet (#AC)	22			
ASK (millions)	2608,38			
Year	1999	2009	2009/ASK	
	ME	ME	ME	
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 (-7176,49%)	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 (-604,49%)	25,987	33,731	0,0129	11,40%
	ME			
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/lbhr)	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)	73904,13			
Year	2009	2009/ASK		Change
	ME	ME		%
Total Operating expenses	2,849,334	0,038	100,00%	
Fuel	1,257,062	0,0166	44,12%	-9,68%
Staff	309,296	0,0041	10,86%	-385,78%
Depreciation	256,117	0,0034	8,99%	-433,26%
Maintenance	66,811	0,0009	2,34%	-575,28%
Marketing	12,753	0,0002	0,45%	-7176,49%
Renting	78,209	0,0010	2,74%	-40,30%
Route	286,559	0,0038	10,06%	-173,87%
Airport fees	443,307	0,0058	15,56%	-147,01%
Other	139,140	0,0018	4,88%	-604,49%
	ME			
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/lbhr)	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
	MS	MS	ME	ME		%
Total Operating expenses	1,434,7	1,436,0	1,031,8	0,0509	100,00%	
Fuel	220,0	228,2	164,0	0,0081	15,89%	-125,04%
Staff	397,5	397,9	285,9	0,0141	27,71%	-40,60%
Depreciation	33,4	33,4	24,0	0,0012	2,33%	-1421,67%
Maintenance	197,4	197,6	142,0	0,0070	13,76%	17,38%
Marketing	25,7	25,7	18,5	0,0009	1,79%	-1243,66%
Renting	197,1	197,3	141,8	0,0070	13,74%	382,72%
Route	96,2	96,3	69,2	0,0034	6,71%	-203,57%
Airport fees	59,6	59,7	42,9	0,0021	4,15%	-583,82%
Other	199,8	200,0	143,7	0,0071	13,93%	-82,56%
	ME					
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					-41,49%
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/lbhr)	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
	ME	ME	0		%
Total Operating expenses	2,623,1	2,884,7	0,0496	100%	
Fuel	807,2	887,7	0,0153	30,77%	-19,18%
Staff	306,6	337,2	0,0058	11,69%	-241,92%
Depreciation	55,4	60,9	0,0010	2,11%	-1620,07%
Maintenance	161,6	177,7	0,0031	6,16%	-94,79%
Marketing	47,0	51,7	0,0009	1,79%	-1277,56%
Renting	116,2	127,8	0,0022	4,43%	51,78%
Route	232,3	255,5	0,0044	8,86%	-135,71%
Airport fees	737,4	811,0	0,0139	28,11%	-3,63%
Other	159,4	175,3	0,0030	6,08%	-329,13%
	MS	ME			
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/lbhr)	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 11 Input data for comparitive value analysis of typical medium range commercial jet aircraft

With the weights of the trade criteria determined it is time for the calculation of the figure of merit for each design option. The determination of the figure of merit is performed as is stated in Figure 2, and a figure of merit is obtained for each individual design option for each airliner component. The determination of the figures of merit is again performed by using pair-wise comparisons and the resulting eigenvector. For the regulations and requirements criteria the design options are compared against each other and a judgement is made on how capable the design options are with respect to the others in adhering to the regulations or helping to achieve the requirements. For the value part of the figure of merit the value model is used. In the value model calculation the design options are again compared to how they perform compared to the others. When all items of the value model that relate to the design option are filled in the model returns a total amount of value number. This number is used to see how much better (or worse) one design option is over the other.

Once the comparisons of all design options are completed they are put into the separate comparison matrices for regulations, requirements and value. The eigenvalues are obtained, the consistency ratios are checked and finally the eigenvectors are obtained. The values in the eigenvector correspond to the figure of merit for the design option and once all eigenvector entries for the regulations, requirements and value matrices are added the total figure of merit for the design options is obtained.

4 Validation Value model

The validity of the value model is established by comparing three competing aircraft with respect to an older generation aircraft. The Boeing 737-200 operated by Ryanair is chosen as reference aircraft and the quantification of value is carried out for a next generation Boeing 737-800 also operated by

Ryanair, while the Embraer ERJ-145 is operated by ExpressJet and the Airbus A320 is operated by EasyJet; with the input date presented in Table 11.

4.1 Comparison first to next generation aircraft family model (737-200/800)

In this case the early Boeing 737-200 operated from 1994 to 2005 by Ryanair[23,24] is compared to a last generation Boeing 737-800NG also operated by Ryanair today[25,26]. The output of the VOM application is presented in Table 15; and further explained in Section 5

4.1.1 The cost related to the aircraft

Cost control and cost breakdown is difficult to measure between a range of models as it is Carrier dependent. The operational efficiency of the processes of a Carrier is reflected in the Total Operating Costs (TOC), which can be found in the Carriers annual papers. Therefore Ryanair is chosen as a carrier to compare both models in the same operational environment. In 1999 more than 80% of the Ryanair total fleet of 22 aircraft[24] consisted of B737-200 aircraft[27]. Today (in 2009) the fleet consists only of 181[24] next generation B737-800 aircraft[27].

The interest costs and insurance costs are dependent on the list price of the aircraft. The list price is recalculated to its Net Present Value (PV) by taking inflation into account. Consequently, the PV of a Boeing 737-200 equals 55.79m$[28], while the PV of a Boeing 737-800 equals 75.30m$[29]. Therefore, using the VOM approach the 200 variant is assessed to be 35% cheaper than the next generation 800 model in today's US dollars; relative to the Cost Lever. All the operating cost factors are then expressed in euros per ASK.

4.1.2 Aircraft utilization

To determine the aircraft utilisation values, typical aircraft characteristics are used. Due to the higher stage-length of the 800 series, the utilisation of that aircraft is higher at 9.59 hours/day versus 6.47 hours a day. The 200 variant has an average stage-length of 229 nautical miles while the 800 variant has an average stage-length of 654nm[30]. The boarding and de-boarding time of a B737-800 takes 55 percent of the total turn-around time of the aircraft[31]; where the smaller capacity of the 200 series (130 pax @ 29inch versus 189 pax @ 29inch) can decrease the overall turnaround time by 25 percent.

		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

Table 12 Results from the VOM application for the reference aircraft

4.1.3 Sustainability of the aircraft

The future use of composite or newly conceived materials may have a significant impact on the recyclability of the aircraft, while diminishing pollution during the life of the aircraft is of course also important. Relative to Thrust Specific Fuel Consumption (TSFC), the lower the TSFC, the higher the efficiency and the lower the fuel consumption per unit weight and so 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[32]. Adjusted for the aircraft cruising thrust (19.00kN thrust for the 200 series versus 24.39kN for -800 series), fuel consumption per passenger for the 200 and 800 twin engine series equal 23.85kg/h and 14.73kg/h respectively.

In considering the noise levels of the next generation engines and airframes, these are also much lower than those of first generation aircraft. The 800 series is rated 80EPNdB[33] while the B737-200 is rated 95.3EPNdB[34], a decrease of 16%. Similarly, the efficiency during take-off, landing and cruise conditions are mainly governed by *SFC* ($C_{l,take\text{-}off}$, $C_{l,landing}$) and during cruise, the thrust-to-weight ratio is another important factor as is represents the inverse of the lift-to-drag ratio (or the efficiency of generating lift). The 800 series has in all four cases better values (0.779; 2.070; 2.730; 0.277 respectively versus 0.56; 2.200; 2.960; 0.279). Other chemical compounds produced during combustion, such as NO_x, SO_x, soot etc; are also compared with respect to the SFC of the aircraft models.

4.1.4 Market requirements

The seat pitch is for both airliners is set on ‘high density’ capacity (29 inch). Inboard entertainment is not provided for the low fares airline and both aircraft have 2 doors available for boarding (one in the front of the cabin and one in the back), while catering, shopping and seat reservation are operated in the same way. However, due to the larger capacity of the B737-800; boarding times are increased for the same flow of passengers but the 800-series has more cargo volume allocated per passenger (0.25m³) than the 200 series (0.19m³).

4.2 Comparison with other aircraft (737-200/ ERJ-145/A320)

After the comparison of the two aircraft in the previous section, this section will expand the validation of the value model with the addition of further two aircraft. The focus of this analysis was to find two airlines operating a large, preferably single type fleet, so that we could compare their performance relative to the Boeing 737-200 that was operated by Ryanair. The selected aircraft are the Embraer ERJ-145 operated by ExpressJet[35] and the Airbus A320 operated by EasyJet[36].

4.2.1 Embraer ERJ-145

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, this includes both the ERJ-145 and ERJ-145XR type and offered 20287.39 million available seat kilometres (ASK’s)[37].

4.2.1.1 Cost related to the ERJ-145

The 2008 Annual Paper[37] provides the necessary data for the cost related to the aircraft of the Embraer ERJ-145(XR). The cost, published in 2008 dollars, are first corrected for inflation[38] and then converted to Euros based on the currency exchange rate at December 31st 2009[39]. Because the regional jets are leased instead of owned by ExpressJet, the depreciation does not include the full depreciation of the aircraft fleet. Therefore the *aircraft cost*, which is the sum of depreciation and renting, is used for the value model. Just like with the Boeing 737’s the purchase price[40] of the Embraer forms the basis for the interest and insurance cost. All the operating cost factors are then expressed in Euros per ASK and compared to the Boeing 737-200 which forms the benchmark of this analysis. With respect to the 737-200, the ERJ-145 scores more value points in the section related to the cost of the aircraft.

4.2.1.2 Aircraft utilization of the ERJ-145

The ERJ-145 provides a capacity of 50 passenger seats and a maximum range 1550nm[41], 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 and an average stage length of 594 miles[37]. The advantage of shorter turnaround time is clearly expressed in the high value points for aircraft utilization.

4.2.1.3 Sustainability of the ERJ-145

The two Rolls-Royce AE 3007A1E engines have a noise level of 77.9 EPNdB[42] and a specific fuel consumption of 0.63 lb/lb/hr[43]. The thrust at cruise altitude is required in order to calculate the fuel consumption during cruise, and therefore 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 and by using the ideal gas law $\rho = p / Rt$, the thrust can be scaled with altitude h with respect to sea level:

$$\frac{T_h}{T_{sl}} = \frac{p_h t_{sl}}{p_{sl} t_h} \tag{12}$$

Assuming sea level conditions with $p_{sl} = 101325 Pa$, $t_{sl} = 288.15K$ $T_{sl} = 7040 lbs$ [44] and cruise conditions at $h = 35000 ft$ with $p_h = 23841.8 Pa$, $t_h = 219.05K$, Equation 12 yields a thrust at cruise conditions T_h of 2179.1lbs which equals 9.692kN: yielding a fuel consumption of 37.54 kg/hr/seat. Due to the lower seat capacity, this fuel consumption per seat is higher than for the 737's. Although the ERJ-145 is quieter than both the 737's, due to the higher weighting factor of fuel consumption per seat in the value model, the ERJ-145 receives lower value points for sustainability.

4.2.1.4 Market requirements of the ERJ-145
Although the ERJ-145's cargo hold volume[45] per passenger is lower than the 737's, the boarding and check-in time is due to the lower capacity much shorter. The boarding and check-in time has a high weighting factor in the model, therefore the ERJ-145 scores better than both 737 on this particular aspect.

4.2.2 Airbus A320 family
EasyJet, Ryanair's biggest competitor, operates a large fleet of 181 aircraft which includes not only 164 Airbus A320 family aircraft but also 17 Boeing 737-700[46]. 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 it is 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.

4.2.2.1 Cost related to the A320 family
The operating cost for the A320 family are based on EasyJet's 2009 annual paper[46] and these figures are converted from pounds sterling to euros based on the currency exchange rate at September 30th 2009[47], at EasyJet's financial year-end. The costs are then expressed in Euro per ASK and compared to the Boeing 737-200. The purchase price which is used in this analysis is the average sales prices in 2008 for the A319[48]. Similar to the situation of ExpressJet, EasyJet does not own all of its aircraft, so the *aircraft cost* accounts for the depreciation in the value model. Relative to its competitor, the 737-800, the A320 scores worse in terms of cost in the value model due to the higher cost of crew, maintenance and administration. Not surprisingly, the A320 scores significantly better when compared to the older 737-200.

4.2.2.2 Aircraft utilization of the A320 family
EasyJet's aircraft have a weighted average capacity of 160 passengers based on their fleet composition[49] and maximum range of 3700nm[50]. In 2008-2009 EasyJet achieved an average utilization of 11 hours and an average stage length of 684 miles[46]. Due to the high utilization figures, the EasyJet's A320 scores slightly higher than Ryanair's 737-800.

4.2.2.3 Sustainability of the A320 family
The two CFM56-5 engines have a noise level of 79.5 EPNdB[42], which is similar to that of the 737-800. Its specific fuel consumption of 0.596 lb/lb/hr[51], which together with a thrust at cruise conditions

of 22.2kN[51], yields a fuel consumption of 16.87kg/hr/seat. Because this is slightly more than the 737-800, it scores less value points in the value model for sustainability.

4.2.2.4 Market requirements of the A320 family

The A320 family features the smallest cargo hold volume[52] of all aircraft in this analysis. However the lower passenger capacity theoretically yields a lower boarding and check-in time. The A320 therefore score slightly higher than the 737-800, but still lower than the 737-200.

5 Discussion

The Boeing 737-800, Embraer ERJ-145 and Airbus A320 have been compared with respect to the Boeing 737-200. To summarise the results; the Embraer resulted in 27.6% increase in value, the Airbus A320 in a 54.6% and the Boeing 737-800 in 69.5 %.

5.1 The Model

The inputs of the value model are linear (e.g. noise reduction is a logarithmic scale but is used as a linear comparison with respect to comparison aircraft). Also linear relations are assumed between the parameters, where the insurance and interest costs are related to the purchase price; whereas external factors will also influence these parameters. The turnaround time is also dependant on the boarding time, which is linearly dependent on the amount of passengers to be loaded/carried. Within the model, there are no differences in depreciation on property and flight equipment, as details of the cost structure are as yet unknown and not modelled currently.

In comparing the four aircraft, no specific flight envelop is set and each aircraft is compared with respect to its mission set by the respective airline. The Direct and Indirect Operating Costs are not only aircraft dependent but differences in the business models and operating plans of the Carriers may result in fluctuations in the costs related to the aircraft (without also taking into account local regulations). However, due to the implementation of sustainability, utilization and market requirement, this model does not only indicate value changes from a technical perspective, but also takes the increase in business value into account. Efficient operations and economies of scale also play an important role in this model.

5.2 AHP

The main aspect of AHP is the pair-wise comparison of each trade criterion and design option and the presented research is limited to some extent by the accuracy and high level nature of the data available to populate this analytical approach. AHP has been implemented as suggested in a linear manner, which seems simplified although the authors propose that this is a very acceptable characterisation of such a subjective relationship involving value, but limitations of AHP due to the use of linear relations in the figure of merit function are well pointed out by Collopy[53]. This limitation has the consequence that the AHP can only be used in a trade-off with existing components that by themselves are suitable for the task they are selected for.

5.3 737-200 vs. 737-800

The results of the value model analysis between the Boeing 737-200 and 737-800 show a very high value increase. Since these aircraft were operated by the same airline, one could state that the validity of the value model between these aircraft is the highest and most significant evidence of validity. The aircraft improvement is due to the technological advancements that were carried out; including: SFC, weight/pax, noise, higher utilisation rate, lower maintenance costs, lower depreciation of the aircraft results in higher business value, etc.

5.4 737-800 vs. A320

It seems that the outcome of the proposed VOM methodology is quite realistic since the gap between the Boeing 737-800 and Airbus A320 is very small, interestingly. The most important difference between the B737-800 and A320 is the cost of maintenance between the aircraft. Since Ryanair has a very small aircraft life cycle and recent fleet, the maintenance costs between both carriers (Ryanair and EasyJet) are not comparable. Moreover, the '*U.S. Department of Transportation: form 41'* claims that the Boeing 737 maintenance cost are up to 35% lower than the A320[54]. When this change is artificially applied in the model, the A320 yields a 61.4% value increase which is still lower but approaching the 737-800's value increase.

5.5 Embraer

The results for the Embraer ERJ-145 show that it yields a high utilization value, due to short turnaround, boarding and check-in times. The performance per ASK are, however, much lower than compared to the other aircraft because of its lower seat capacity and average stage length. Overall the ERJ-145 is shown to be significantly less valuable when compared to the 737-800 and A320.

6 Conclusions and Recommendations

After the application to four aircraft and taking into consideration the assumptions and limitations of this model, the Value Operations Methodology yields a realistic output that supports Value Driven Design (VDD). The comparison of the older Boeing 737-200 with the next generation Boeing 737-800 shows large improvements, both from a technical and operational perspective. The comparison with the Embraer ERJ-145 shows that while the utilization value is very high, its performance per ASK is rather low and thus is herein valued less than when compared to the larger aircraft. Finally, the comparison between the Boeing 737-800 and the Airbus A320 shows that there is a large difference in maintenance cost, while on the other value aspects utilised these two aircraft are strong competitors. In order to increase the validity of the model, an evaluation should be carried out by comparing the aircraft within a specified flight envelop. The results which roll out the model have linear relations. In reality, parameters might have exponential or logarithmic characteristics.

The most fundamental conclusion from the work presented is actually that the VDD approach simply promotes 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 result in a loss of control on managing the desired systemic output. 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 re-focus of VOM within VDD 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 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 in the blood of every CEO and most of the best engineers but this has never been formalised in an integrated and accepted manner. That (commercial stakeholder position) will be on a financial and competitive basis whereas this paper has considered even wider application, to show that this is opening up a significantly different approach to aircraft design methodology that may well help us sustain this great innovation beyond many of its current environmental challenges, which may well be still financial but of a much more holistic cause: proactively rather than reactively!.

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