DESIGN FOR CUSTOMER

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Abstract

Commercial aircraft design is steadily evolving through customer driven design strategies embracing technology, manufacture/ assembly, operation/support and various management considerations (a multitude of 'Design for....' considerations). This paper attempts to consolidate the various 'Design for ...' terms in a unified manner for lowest Life Cycle Cost in an Integrated Product & Process Development environment, leading into what is termed as 'Design for Customer'. The paper examines the role of cost effectiveness through seven industrial manufacturing case studies and demonstrates their merits through operating cost reduction. The trade-off studies indicate that 0.55% percent savings in Direct Operating Cost can be achieved for a 1% cost reduction in aircraft cost, for the Airbus 320 class of aircraft. The main contribution is the formulation of two new indexes: 'Value for Design' and 'Value for Customer' which measure design merit in terms of the customer.

1 Introduction

As early as in the late Eighties, commercial aircraft design was more driven by customer demands for reduced cost and lead-time than by technology by itself [1]. In the last three decades, the free world man-hour rates have risen by four to six times, resulting in an aircraft price hike, e.g. typically by six for the Boeing 737. Naturally, there have been advancements in the design and operational capabilities. Fuel prices have also fluctuated and air travel became cost sensitive. Typical aircraft Direct Operating Cost (*DOC*) breakdown shows that the aircraft cost contribution to *DOC* is two to four times higher than the contribution made by fuel cost [2]. The airlines have sent out the signals to industries that unless aircraft price is reduced, could become untenable. The paradigm of 'Better, Faster (delivery time), and Cheaper to market' is replacing the old mantra of 'Higher, Faster (speed), and Farther' [3]. The growing customer demand to reduce cost and lead-time as the main drivers in commercial aviation has to be tackled at the conceptual design phase in order to produce 'right first time' competitive products. Aircraft manufacturing companies are meeting the challenges of this new paradigm by assessing how they do things, discarding old methods and working practices for newer re-engineered alternatives. This has been witnessed first hand from the shop floor experiences of the first author as Chief Aircraft Designer of a large aerospace company.

The shift of paradigm from the classical aeronautical considerations (aerodynamics, structures, propulsion, systems) has to the appearance of new terminologies, more so from the academic/consultant circle. These include: Design for Manufacture, Design for Assembly, Design for Quality, Design for Six Sigma, Design for Life Cycle, Design for Cost, etc; heading towards a generic Design for X. However, are not all of these terms interdependent in catering for customer driven design? Academic theories may add new insight but many prove difficult to implement in industry. The post September 9 steep downturn in business demands opening up new frontiers of interest such as the role of cost effectiveness at every level. From the emerging geo-political scenario, new technological considerations, e.g. on sustainable development, anti-terrorism design features etc, are to be taken into account. This paper treats all of these considerations in a *holistic* manner, which facilitates such studies where industrial and operational data is lean [4].

The importance of engineering costing within aircraft design is playing a more rigorous role [5] as an integrated tool embedded in the multi-disciplinary systems architecture that promotes 'best value'. Differential evaluation of product cost and technology, offering reliability and maintainability along with risk analysis, are important considerations in cost management. Cost details also assist preliminary planning for procurement and partnership sourcing through an efficient bid process. The final outcome is to ensure that the acquisition of aircraft has been driven by the balanced trade-off between cost and performance. This will lead eventually to ensuring affordability and sustainability for the operators over the product life cycle.

The new challenge for industry is to look into all aspects of ownership cost at the conceptual stages. A performance evaluation based on setting individual goals of cost minimisation at each '*Design for…..*' consideration may not bring out the global minimum when strong interactions exist within the multi-discipline [6]. In an Integrated Product & Process Development (*IPPD*) environment within design (Design-Build teams working by Concurrent Engineering), the combined effort of various disciplines will provide a better approach to making the product 'right-first-time' in terms of lower manufacture and operational cost. This leads us to the introduction '*Design for Customer*' and its associated indexes. The importance of a global minimum that produces a '*satisfying*' design is stressed, rather than the separate minimisation of individual costs through the separate design considerations. Consequently, a robust and rapid cost model can be provided to support trade-off studies in arriving at the predicted 'best value'.

2. The '*Design for Customer'* Considerations

The various design considerations, generalised as '*Design for Customer*' terms, can be broadly classified under six categories, as presented in the sections below with brief descriptions of the sixteen aspects therein. These design considerations require the designer to be provided with the relevant multidisciplinary information for the product at the conceptual stages, as anticipated using expertise knowledge and available technology levels. Of the sixteen '*Design for Customer'* aspects listed, only the most influential are addressed herein. These arise from *DFM/DFA* considerations while another relates specifically to performance; although the latter is related to manufacturing capability through the inclusion of drag.

2.1 Technology Drivers

1. *Design for Performance*: This includes input from the classic aircraft design considerations: aerodynamics, structures, propulsion and systems being considered to minimise fuel consumption. This is a mature technology for generic subsonic commercial aircraft design but there is diminishing return on higher investment that incorporates advancement.

2. *Design for Safety*: Crashworthiness, damage tolerance, and emergency evacuation etc have also become mature technologies but are sensitive to ground rule changes.

3. *Design for Component Commonality*: The family concept of derivative aircraft design does considerably benefit from cost reduction by maintaining a large degree of component commonality within the variants. Derivative designs can cover a wider market at a much lower unit cost as amortisation of the non-recurring cost is distributed over a larger number of units sold. However, some of the variant aircraft designs may not be sized to the least-fuel burn condition, although the lower unit cost more than compensates the affect on *DOC*. This consideration is crucial for the success of the product range.

2.2 Manufacturing Drivers

4. *Design for Parts Manufacture* (*DFM*): This study concerns the appropriate process required for part manufacture [7]. The trade-off includes: cost versus material selection; process selection; use of CNC machines; part commonality and modularity considerations that facilitate assembly etc. One of the key issues at the conceptual design stage is to have a low part count that reduces assembly time. However, the lowest part count approach may not be the cheapest method.

5. *Design for Assembly* (*DFA*): This concerns the lowest man-hours required to assemble the parts [8]. Traditional practices in the aircraft industry has lead to the design of assemblies that consist of numerous components, creating a complex organisational structural in the engineering, logistics and management disciplines. It also results in an inefficient use of factory space, and quality is often compromised due to the unnecessary operations and fasteners required to join the mating parts. The aim of *DFA* is to minimise manufacturing cost through optimised methods engineering with innovative '*Best Practice Techniques*' for the jigs and tool design, whether manual or computerised. Here, the product configuration and its detailed parts' design play an important role.

6. *Design for Quality* (*DFQ*): The essence of quality control is in adhering to the desired specification requirements. One such example is the aerodynamic surface smoothness requirements that are achieved through the surface tolerance specifications at final assembly. Currently, many quality issues are tackled at the post-conceptual design stage.

DFM/DFA/DFQ concepts are not a stand-alone concepts and there is a direct relationship between *DFM* and *DFA* when achieving lower cost of production whilst maintaining quality (*DFQ*). Considering that a civil aircraft contains large number of parts, a measure of the relative ease of product assembly plays a very prominent role in determining producability [9].

2.3 Management Drivers

7. *Design for Six Sigma* (*DFSS*): This represents an integrated approach to design that reduces the possibility of mistakes/inefficiencies, making the product 'right-first-time' and preventing waste of company resource [10]. It is a management driven task to extract more from the employees and to improve routine procedures. It becomes an integrated engineering approach to design when the product is manufacturable at the highest quality and lowest cost whilst satisfying all of the customer requirements. Six Sigma aims to expose the "hidden factory" of waste by addressing product and manufacturing problems.

8. *Design for Cost*: This raises the dilemma of the definition between 'Design to Cost (*DTC*)' and 'Design for Cost (*DFC*)', or whether both should be considered. However, the tendency of management to emphasis *DTC*, e.g. in Lean Manufacturing, can be counterproductive.

2.4 Operational Drivers

9. *Design for Reliability and Maintenance (R&M)*: The design must guarantee integrity with high-time between failure and repair in a specific low downtime. While the avionics and engines come with well-studied *R&M* status, many other aircraft components (mainly structures with large built-in redundancy, etc) have yet to evolve in address such issues at the conceptual design stage. Currently, a considerable amount of maintenance resource is planned after the design has been made and is acquired to meet that requirement. This arises from the difficulty of translating *LCC* feedback; typically being of a statistical nature from the more abstract operational arena. Cost trade-off studies considering reliability, reparability and fault isolation are key aspects at the conceptual design stage. Reliability is the most important consideration to improving the support environment; in generic terminology yielding a more *robust* design. Fielding [11] summarises some selected *R&M* studies, mostly on interfacing systems and bought out items.

10. *Design for Logistic Supports*: This is an operational aspect with second order impact on aircraft design. The existing support system caters for most of the logistic details without infringing any major changes required in aircraft design outside of unusual situations. Early input from the operators for any design consideration does also help controlling cost.

11. *Design for Training & Evaluation (T&E)*: This is an area that is currently not under strong consideration at the conceptual design stage. Aircraft *DOC* estimation does not include the cost of *T&E*. Design considerations such as commonality concepts, modular concepts etc., could reduce *T&E* costs and therefore need to be assessed at an early stage.

12. *Design for Ground Based Resources*: This may also be considered of lower order consideration at the conceptual stage, unless special purpose equipments are required (see next section). In general, ground-based support resources are being standardised and can be shared by a large fleet in distributing the cost of operation.

13. *Design for Special Equipments*: If any special purpose equipment has to be introduced for ground-based serviceability then cost trade-off study at the conceptual design stage would prove beneficial. However, this *LCC* consideration has more meaningful impact in the military sphere.

2.5 Environmental Drivers

14. *Design for Ecology*: Since the Seventies, environment issues, such as anti-pollution have been enforced through government legislation on noise and emissions (fuel dumping not permitted now) at an additional cost. This is a relatively matured technology with diminishing returns on investment for improvement till more stringent legislation emerges.

15. *Design for Recycling*: Aerospace technology cannot escape from the emphasis on recyclability; an issue gaining strength as can been seen from the topical agenda of 'sustainable development' in recent UN summit meetings. Design for stripping is an integral part of the Design for Recycling, which minimises the cost of disassembly. New materials (both composites and metals) bring additional considerations in terms of disposal. Cost trade-off studies on *LCC* versus material selection for recycling could infringe upon marginal gains in the weight reduction or cost of fabrication.

2.6 Security Drivers

16. *Design for anti-terrorism*: In-flight safety features incur additional cost through protecting against terrorist activities, e.g. with the use of expensive explosion-absorption airframe or the provision of cabin isolation features through compartmentalisation, etc. These considerations are yet to evolve to be incorporated at the conceptual design stage.

3. Manufacturing Considerations

The focus of this paper is on the impact of customer demands on aircraft design and the approach taken in dealing with that. The manufacturing equipment and processes of the producer set a baseline in terms of their capability to meet design requirements. In preparation for the case studies presented in there following section there are two best practise procedures in particular to consider: *Jig-less Assembly* and *Flyaway Tooling*. These vary from company to company and contract to contract and cause variance in design-oriented studies herein presented.

1. *Jig-less Assembly*: During the civil aircraft development phase, tooling costs account for more than a third of that cost. *Jig-less assembly* [12] reduces cost and increases the flexibility of tooling systems through the minimisation of non-recurring costs of product-specific jigs, fixtures and tooling. Also there is significant reduction of time from concept to market. *Jig-less assembly* does not mean tool-less assembly, rather, the eradication or at least reduction of jigs. Simple fixtures may still be needed to hold

the parts during particular operations but other methods are being found to correctly locate parts relative to one another. Assembly techniques are simplified by using precision positioned holes in panels and other parts of the structure to "self locate" the panels. This process, known as determinant assembly uses part-to-part indexing, rather than the conventional part-to-tool systems used in the past.

2. *Flyaway Tooling*: Within the airframe manufacturing industry, it is generally accepted that approx. 10% of the overall manufacturing costs of each airframe can be attributed to the manufacture and maintenance of assembly jigs and fixtures. Traditional 'hard tooling' philosophy requires that the desired quality of the finished structure be built into the tooling. The tooling must therefore be regularly calibrated to ensure build quality. The alternative philosophy of *Flyaway Tooling* [13] has been conceived to reduce tooling costs and improving build quality. This approach envisages that future airframe components will be designed with integral location features that incorporate positional datum which transfer into the assembly. This will enable in-process measurement and control, while also aiding in-service maintenance and repair. It may also be possible to design aerospace structures with sufficient inherent stiffness so that the assembly tooling can be reduced to simple, reusable and re-configurable support structure.

4. Indexes in 'Design for Customer'

The holistic approach of this paper suggests the role of cost modelling as a tool to address all of the considerations simultaneously. This facilitates performance/requirement versus cost trade-off studies to arrive at the most 'satisfying' product line with the widest coverage for customer. Two measuring indices, (i) '*Value for Design*' and (ii) '*Value for Customer*' which measure the merits of the product are introduced. They are interrelated and measure specific parameters.

In this paper, *DOC* substitutes *LCC* as in commercial aviation *DOC* constitutes the bulk contribution. While the constituent elements of *DOC* is standardised by associations on both sides of Atlantic, the *LCC* computational ground rules are yet to be standardised and varies from operator to operator. There is lack of *LCC* data in the public domain, while *DOC* can be computed by using standard ground rules, herein by the Association of European Airlines.

To use the formula, a set of standard parameters is to be established for the baseline aircraft in the class (payload-range) to compare with competition. The parameters of competition for aircraft in the mid-range and above class should not differ more than ±15%, remaining within a linear range of variation. Truly, this is not linear but the linear simplification provides good insight through comparison at the conceptual stage of design. The formulae need to be further refined for smaller aircraft such as business-jet class, while the payload-range variation within the smaller class are much greater. The standard parameters of interest are denoted with an asterisk * as follows: DOC^* in US Dollars per seat/nm, aircraft unit cost UC^* in million US Dollars, delivery time t^* in years (from the order placement), payload P^* passenger number, wing loading $(W/S)^*$ in kg/m^2 and total take-off thrust to aircraft weight ratio $(T_{SLS}/W)^*$.

The operational Life Cycle of the aircraft is taken as 10 years, with a residual value of 20% of the original aircraft cost. To evaluate variant designs, these have to be normalised to a baseline design. *DOC* levels out well before it reaches the design range so that a variation of around ±15% in range can be neglected. With small changes in range, the utilisation hours are also kept invariant within the class when evaluating the indices.

The baseline aircraft designs are associated with best 'Lift to Drag' (*L/D*) ratio at mid-cruise weight (Long Range Cruise condition). Normally, the *L/D* characteristic is relatively flat and derivative designs (in the family) within the linear range of ±15% variation would still have an *L/D* that is close to the maximum design value of the baseline aircraft. The Breguet Range equation indicates that range is proportional to the square root of *W/S*.

A shortened variant with a lower payload and range will have a lower *W/S* and a de-rated engine. Such an aircraft is then oversized with more wing area than is required. It will have a better take-off performance but a slightly degraded range performance. On the other hand, the extended version will have more payload; its weight control may have to be traded off with the range capability, and the take-off mass invariably increases thus requiring up-rated engines, especially in compensating the take-off performance that suffers from the higher *W/S* (undersized wing). It is for this reason that the competition aircraft parameters affecting the indexes need to be normalised to baseline standards for comparison.

These comparative formulations satisfy the customer's operational requirements in terms of product usefulness through unit cost, operational cost and time to meet demand. From this definition, an increase in the value of the product will be achieved; through improved performance (Better), lower cost (Cheaper), and shorter times (Faster delivery). It will become evident that *DFM/DFA* methodology contributes directly to lower cost, improves quality and reduces manufacturing cycle time, thereby increasing the value of the product.

4.1 Index for '*Value for Design*'

The first definition compares design merit by establishing an index. The *Value for Design* K_u is directly proportional to T/W and W/S and inversely proportional to *DOC, UC* and a lead time t^*. Then value of K_u increases (greater than 1) with merit:

$$K_{u}, = \frac{(DOC^*/DOC)\times[(T/W)^*/(T/W)]\times\sqrt{(W/S)^*}}{\sqrt{(W/S)}\times(UC/UC^*)\times(t/10t^*+0.9)}$$

4.2 Index for '*Value for Customer*'

Aspects of the *Value for Design* K_u are used to compare the merit of the design itself while operators' wish to compare the operational cost saving between designs is also incorporated in *Value for Customer*. Again, K_n increases with merit (+ positive value):

$$K_n = [DOC^* \times Unit\ Cost^*] - [DOC \times UC \times (P^*/P) \times (t/10t^*+0.9)]$$

5 'Design for Customer' Case Studies

Seven case studies are introduced in the paper. However, all of the data supplied by Bombardier Aerospace-Shorts (BA-S) is presented in non-dimensional form to protect propriety integrity. The case studies are varied in nature and specific relevance to the subsections within Section 2. They relate to the design and manufacture domain and encompass the most fundamental aspects of Design for Customer: *DFM, DFA*, *DFQ*, *DFSS* and *Design for Performance*.

5.1 Engine Nacelle Nose-cowl Design

A case study of the airframe that makes up the '*Nose Cowl*' of two nacelles, identified as nacelle A and nacelle B within the same family of aircraft and engine, has been carried out [5]. Nacelle A is an earlier product and is taken as the baseline design. Nacelle B, as a variant design, is a subsequent product and is of higher standard of specification. Noting commonality within that family of designs, the study presents a detailed comparative cost study of the two geometrically similar nose cowls; addressing the complexity of multidisciplinary cost drivers. While the aerodynamic mould-lines of both the nacelles are similar, their structural design philosophy and resulting sub-assembly (tooling concept) differ. The results show that although geometrically similar, nacelle B with 13.5% higher thrust engine could be produced at 8.5% lower cost through *DFM/DFA* and *DFSS* considerations.

5.2 Flight Control Pressure Box Design

The design for ease of assembly methodology *DFA* employed in aircraft manufacturing at BAS is yielding significant benefits in the overall value of the components. An example of this is the redesign of a Flight Control Pressure Box, which fits into the pressurised floor section of the 70-seater CRJ700 Canadair Regional Jet [14]. The original design is a typical fabricated aircraft sub-assembly while the subsequent *DFA* solution resulted in a monolithic single part design. The results are summarised in Table 1.

5.3 Fuselage Firewall-Bulkhead Design

An example of *DFM* implementation is the redesign of the firewall bulkhead of a tail-cone on a business jet [15]. The purpose of the Firewall is to resist excessive heat that may emanate from a malfunction of the Auxiliary Power Unit (APU). Typically, for such thermal applications, stiffened Titanium structure is used. The redesign centred on the minimization of material usage and reduced machining time: achieving a cost reduction of around 50% and a weight reduction of 6%. A summary of the results is given in Table 2.

5.4 Fuselage Emergency Exit Door Design

The redesign of a manufactured over-wing emergency exit door was being carried out for a new derivative of the parent aircraft [16]. The original design consisted of a wholly sheet metal riveted structure onto which the exterior skin was riveted. It was deemed satisfactory. However, it was also deemed that the door was over-expensive to make due to the excessive part and fastener counts, and therefore, that a *DFM/DFA* approach would be especially relevant. A number of alternative manufacturing processes where considered in addition to variants on the original design. Primarily, the use of investment casting or high speed machining was considered, for redesigns of both original and reduced part counts. A single-piece casting was considered for the main structure of the door but was rejected due to damage tolerance issues and poor crack stopping, as well as uncertainty regarding process capability (tolerances). The high speed machining option was chosen as the best solution, in conjunction with some sheet metal fabrication. In terms of cost, the optimal redesign consisted of eight very significant machined parts, including a pair for top and bottom corners. These were geometrically complex and subject to concentrated corner stressing. The impact on cost can be seen from Table 3.

5.5 Nacelle Structural Torque Box Design

A nacelle torque box is the corner stone to the stiffened airframe shape that also provides rigidity under thrust/reverser loading. The results of a *DFM/DFA* study once again demonstrate that such considerations at the conceptual stage of design do save cost [16], as shown in Table 4.

5.5 Fuselage Final assembly Jig Design

DFA is not restricted exclusively to aircraft components. An example of *DFA* analysis at Bombardier Aerospace-Shorts was conducted on the final assembly jig for the forward fuselage section of the Bombardier Global Express business jet [16]. The original design concept had been generated but tooling engineers had experienced problems in getting further manufacturing cost taken out of the jig. The results of the *DFA* analysis are given in Table 5.

5.6 Aircraft Skin Tolerance Design

Research has been carried out [17] into the parametric trade-off study involving manufacturing cost reduction and parasitic drag rise. In terms of the quality of aerodynamic wetted surface, results indicate that there is scope for some tolerance relaxation from the current tolerance allocation to an optimum that maximises *DOC* saving. For the short-medium range mission profile of the Airbus 320 class of aircraft, it was found that the optimal relaxed tolerance allocation would reduce aircraft *DOC* by 0.421%. The results offer considerable insight into a relatively complex problem in a multidisciplinary environment. The 0.421% *DOC* reduction translates into a saving of US$132 per aircraft per sortie. At an annual utilisation of 500 sorties (two sorties a day), the annual *DOC* saving per aircraft in the fleet is US$ 66000. Further work shows the effect of changes in fuel and aircraft cost [15].

6 Analysis and Results

Three examples are studied to demonstrate the logic of the *Ku* and *Kn* numbers, relative to the benefits identified for the seven cases.

6.1 Theoretical *Ku* and *Kn* Analysis

The baseline aircraft (150 passengers for 2800*nm* range) has standard parameters as follows (at 2000 price level): UC^* = \$40 million, delivery time, t^* = 2 years, $(W/S)^*$ = 655.37 kg/m^2 (Takeoff mass being 73500 kg for a reference wing area of 112.15 m^2), $(T_{SLS}/W)^*$ = 0.309 (T_{SLS}/engine being 111250N) and DOC^* = \$0.07075 per seat nautical mile (at \$0.75 per US gallon). The engine *specific fuel consumption* (*sfc*) is kept invariant. Any change in the engine price to satisfy the variant design is also integrated into the aircraft price change.

Example 1: This relates to the upgrade of the baseline aircraft design with some improvement in the weight and *DOC* at an additional cost with earlier delivery time. This has been achieved through *DFM/DFA* efforts that reduced the part count in some major components, thereby reducing weight (approx. 600 kg) and the assembly time to deliver; by just over a month early. The associated parameters of the redesign are as follows: UC = \$40.5 million, t = 1.9 years, W/S = 650 kg/m^2, T_{SLS}/W = 0.3115 (same engine), and DOC = \$0.07 per seat nm.

Value for Design, K_u, =
[(0.07075/0.07) × 1.008 × √655.37]/[√650 × (40.5/40) × (0.095 + 0.9)] = 1.015
This highlights the fact that the redesign offers a better value for the design.

Value for Customer, K_n = 0.07075×40 - 0.07×40.5 × 0.995 = 2.83 – 2.82 = 0.01
This shows that the upgrade is more profitable, even when it costs half a million dollars more.

Example II: A new aircraft design with the same payload and range is considered but having considerably better *DOC*. While the redesign was lighter (70000 kg), the W/S and T_{SLS}/W remained close to the original deign. This helps to contain any aircraft unit cost rise for new designs. The associated parameters for the new design are as follows: *Unit Cost* = \$42 million, delivery time t = 1.8 years, Wing Loading W/S = 650 kg/m^2, T_{SLS}/W = 0.309 (same as baseline) and DOC = \$0.064 per seat nautical mile (≈10% improvement).

Value for Design, K_u, = [(0.07075/0.064)× √655.37]/[√650 × (42/40) × (0.09 + 0.9)]
= 1.068
The index suggests that the new design certainly offers much better value for money.

Value for Customer, K_n = 0.07075 × 40 - 0.064 ×42 × 0.99 = 2.83 – 2.66 = 0.17
To note that the new design is more profitable even when it costs two million dollars more! This requires type change fpr the fleet.

Example III: This concerns a variant design with a lower payload and range (130 passengers and 2500 nm). The associated parameters of the new design are as follows: *unit cost* = \$38 million, delivery time t = 1.8 years, W/S = 600 kg/m^2 (for a takeoff mass of 67290 kg and a reference wing area of 112.15 m^2), T_{SLS}/W = 0.309 (de-rated to equate to the baseline) and DOC = \$0.079 per seat nautical mile. The engine thrust loading is kept the same as the baseline design.

Value for Design, K_u, = [(0.07075/0.079)× √655.37]/[√600×(38/40)×(0.09+0.9)] = (0.896×1.045)/(0.95×0.99) = 0.996
The variant design shows lower value for money by virtue of having an over sized wing. Nevertheless, it would compete well with a design sized wing because of lower investment level and increased commonality in *R&M* and *T&E* (*LCC* components).

Value for Customer, K_n = 0.07075×40 – 0.079×38×1.096×0.99 = 2.83 – 3.43 = -0.6
The baseline design is more profitable to operate but the sector does not offer adequate passenger load factor forcing the operator to use a smaller variant design and yet make profit. The lower range adds to the cause.

6.2 Application to Case Studies - Results

Table 6 summarises the savings made in the seven case studies presented. It can be seen that there is a wide variation in aircraft cost saving depending on the type of *DFM/DFA* and *DFSS* considerations applied. Figure 1 depicts the *DOC* variation with aircraft cost, fuel cost and aerodynamic effects (drag changes). From this graph it is evident that competitive aircraft *DOCs* can be obtained in order to determine the K_u and K_n indexes for assessing design merit.

It has been found that a one percent reduction in aircraft cost through *DFM/DFA* considerations affects the 'Fixed Cost' elements of *DOC* by a 0.55% reduction. If drag increases as a result of cost reduction then the 'Trip Cost' elements of *DOC* (i.e. fuel burn) would also be affected and in that case, the *DOC* reduction is approx. 0.51%, relative to the rise in fuel cost. In general, *DFM/DFA* is also associated with weight reduction that can offset the penalty due to drag increase, if any. The indices are calculated to be, K_u = 1.045 and K_n = 0.11. These show that the '*Design for Customer*' approach has identified the improved design merit that has increased the *DOC* gains.

7 Discussion

The paper presents a holistic approach in consolidating the various considerations into a '*Design for Customer*' approach that aims to lower ownership cost. The *IPPD* process at the early conceptual design phase has to synthesise many trade-offs in order to arrive at a best value for the product as a global optimum rather than optimising to a particular design study.

Two measuring indexes have been introduced, '*Value for Design*' and '*Value for Customer*', as part of a method of assessing the merits of design and operation, respectively. Robust cost modelling is essential to the estimation of the two indexes. However, the authors believe that there is considerable scope for improvement of the semi-empirical formulae for the indexes although there is a general lack of good quality data for correlation. Cost estimation is one of the main tools that the trade-off studies utilise in deciding the technology level and manufacturing philosophy to be adopted. The success or failure of the cost estimation depends on identifying the correct cost drivers and establishing good cost relationships with the available 'in-house' data that ensures accuracy. Currently, public domain data is very lean which suggests that rapid, robust and consistent but simple cost modelling capabilities are appropriate for industrial utilisation at the conceptual design stage.

From the *DFM/DFA* experiences at BA-S, it can be concluded that the best way to approach '*Design for Customer*' considerations is to: 1) reduce the number of components and standardise where possible and 2) ensure that the remaining components are easy to assemble involving low man-hours. Further improvements are sought through the incorporation of a knowledge-based approach, used in conjunction with CAD systems and Assembly Process Simulation software for the planning and verification of the assembly operations. This digital manufacturing approach allows the manufacturing/methods engineers to validate the feasibility of the process plan; determining cycle time, bottlenecks and estimating capital costs. Software can also facilitate the knowledge capture from the manufacturing/methods engineers and so allows them to set accurate and consistent time standards through an automated graphical user interface. Another important feature is an emphasis on establishing the requirements of all customers in the supply chain and not limiting the assessment to the immediate customer. *DFM/DFA* should strengthen the multi-disciplinary team activity approach at all phases of the design process, thus ensuring that the technical expertise of the participants can be successfully utilised. Management strategy such as *DFSS* [18] and Lean/Agile Manufacturing [19] and effective man-management also need to be taken into consideration if improvements are to be met in the areas of assembly system profitability and work environment. The concept of agile manufacturing is driven by the need to quickly respond to the changing customer requirements.

8 Conclusion

The scope of the study demonstrates that benefits can be exploited if the global '*Design for Customer*' approach is applied at the conceptual stage that will allow engineers to work together on the highly complex aircraft systems architecture design in order to better explore cost control and understand the relevant trade-off studies. This result in understanding of how a diverse range of systems work and go on working, and promotes the capture and transfer of best practice and risk management across the operational life of ownership. The concept presented herein stresses the need for interconnecting cost analysis from different disciplines, at an early stage, in order to fully exploit the advantages offered by advanced digital design and manufacturing processes. Cost trade-off studies at the conceptual design stage will lead to a '*satisfying*' robust design with minimal *LCC*. Strong multidisciplinary interaction is essential between the various design departments in attaining the overall (global) goal of minimising cost rather than individual (departmental) minimisations.

The concept of '*Design for Customer*' forces long range planning, helps improve the understanding of systems design architecture and trade-off, and opens out the scope for sustainability and eco-friendliness within the product line. The product passes through well-defined stages during its lifetime e.g. conception, design, manufacture, certification, operation, maintenance/modification and finally disposal at the end of the life cycle. Improved information quality and its management throughout the life-cycle of current products should be sufficiently and comprehensively planned at the conceptual stages of new product line. That is facilitated through Design For Customer.

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Table 1

Metrics	Before	After	Reduction	in percent
Number of Parts	29	1	28	96
Number of Fasteners	346	124	222	64
Assembly Man-hrs	20	3.3	16.7	83
Recurring Mfg Cost (£)	770	459	311	40
Tooling Cost (£)	3863	2847	1016	26

Table 2

Metrics	Before	After	Reduction	in percent
Raw Material (kg)	143	96	47	32
Machine Time (hrs)	138	90	48	34
Weight (kg)	10.6	9.9	0.7	6
Recurring Mfg Cost (£)	17827	8413	9414	52

Table 3

Metrics	Before	After	Reduction	in percent
Number of parts	121	50	71	58
Number of Fasteners	1880	1200	680	36
Assembly Time – hours	61	27	34	55
Weight – lbs	26.5	24.7	1.8	6
Recurring Manufacturing Cost - £	4555	4285	270	6
Tooling Cost - £	338000	45100	92900	86

Table 4

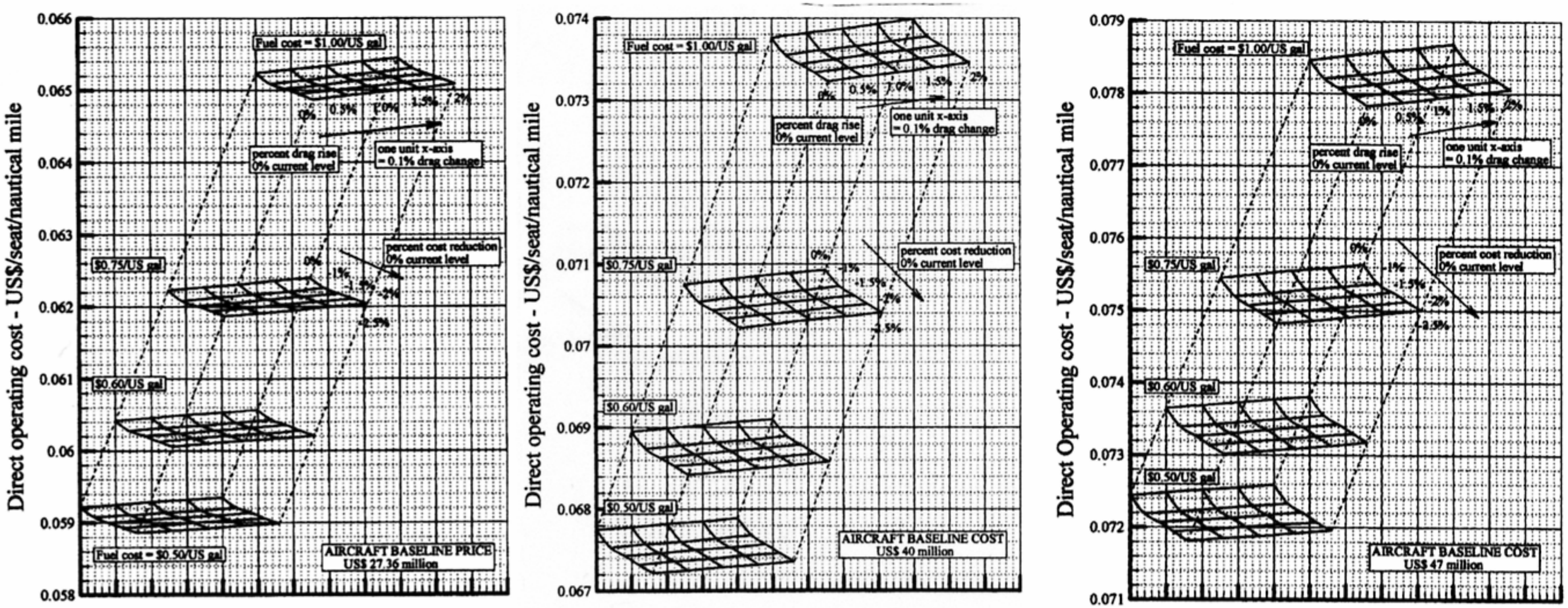
Metrics	Before	After	Reduction	in percent
Number of parts	110	86	24	22
Number of Fasteners	1090	916	174	16
Assembly Time – hours	116	96	20	17
Weight – lbs	8.6	7.1	1.5	17
Recurring Manufacturing Cost - £			500	

Table 5

Metrics	Before	After	Reduction	in percent
Number of Parts	5320	1480	3840	72
Assembly & Manfact. Man-hrs	2970	1730	1240	41
Manufacturing Cost (£)	113600	61500	52100	46

Table 6

Case	% Cost Saving	Remarks
1. Engine nacelle	8.3	DFM/DFA – by 24.13% saving in assembly time.
2. Pressure box	40	DFM/DFA – by 83% saving in assembly time.
3. Tail Cone	52	DFM/DFA – by 34% saving in machine time
4. Exit Door	6	DFM/DFA – most savings in non-recurring cost.
5. Torque box	17	DFM/DFA
6. Jig modification	46	DFM/DFA – most savings in non-recurring cost.
7. Tolerance relax	0.42% in DOC	Aerodynamic and DFA considerations



Aircraft DOC of Airbus 320 class of aircraft