Aircraft cost modelling using the genetic causal technique within a systems engineering approach

R. Curran, S. Castagne, J. Early, M. Price, S. Raghunathan, J. Butterfield and A. Gibson[‡]
Centre of Excellence for Integrated Aircraft Technologies (CEIAT)
School of Mechanical and Aerospace Engineering,
Queens University Belfast,
Northern Ireland, UK

[‡]Aeronautical Engineering,
Massey University,
New Zealand

ABSTRACT

The paper is primarily concerned with the modelling of aircraft manufacturing cost. The aim is to establish an integrated life cycle balanced design process through a systems engineering approach to interdisciplinary analysis and control. The cost modelling is achieved using the genetic causal approach that enforces product family categorisation and the subsequent generation of causal relationships between deterministic cost components and their design source. This utilises causal parametric cost drivers and the definition of the physical architecture from the Work Breakdown Structure (WBS) to identify product families. The paper presents applications to the overall aircraft design with a particular focus on the fuselage as a subsystem of the aircraft, including fuselage panels and localised detail, as well as engine nacelles. The higher level application to aircraft requirements and functional analysis is investigated and verified relative to life cycle design issues for the relationship between acquisition cost and Direct Operational Cost (DOC), for a range of both metal and composite subsystems. Maintenance is considered in some detail as an important contributor to DOC and life cycle cost. The lower level application to aircraft physical architecture is investigated and verified for the WBS of an engine nacelle, including a sequential build stage investigation of the materials, fabrication and assembly costs. The studies are then extended by investigating the acquisition cost of aircraft fuselages, including the recurring unit cost and the non-recurring design cost of the airframe sub-system. The systems costing methodology is facilitated by the genetic causal cost modeling technique as the latter is highly generic, interdisciplinary, flexible, multilevel and recursive in nature, and can be applied at the various analysis levels required of systems engineering. Therefore, the main contribution of paper is a methodology for applying systems engineering costing, supported by the genetic causal cost modeling approach, whether at a requirements, functional or physical level.

1.0 INTRODUCTION

Fundamentally, systems engineering is a holistic approach that is implemented to deliver the most competitive product, in terms of customer requirement, cost and quality. According to the definition given by one of the technical standards[(1)] for systems engineering, it is "an interdisciplinary approach that encompasses the entire technical effort, and evolves into and verifies an integrated and life cycle balanced set of system people, products, and process solutions that satisfy customer need." Systems engineering consists of both technical knowledge processing and systems engineering management, and therefore there is a requirement for tools and models that can predict the impact of technical decision making on emergent behaviour and characteristics such as acquisition cost, time

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to market and life cycle performance. The systems engineering process is typically referred to as "a top-down comprehensive, iterative and recursive problem solving process, applied sequentially through all stages of development"[2]. Consequently, supporting tools would be characterised as being interdisciplinary, multi-level, and flexible in nature.

The paper addresses the need for an approach to cost modeling that will facilitate the development of analysis tools that can operate in complex[3, 4] interdisciplinary environments, which are increasingly being developed with a systems engineering philosophy. The importance of integrating cost into the development process is highlighted in Fig. 1, which illustrates the increasing difficulty in influencing both production and lifecycle costs[16]. Already at the end of the conceptual design phase typically 70% of lifecycle cost is determined while the opportunity to further reduce costs is only 35%. To provide design synthesis, the approach needs to incorporate technical cost drivers that flow-down to the required design level and physical configuration but must also cope with life cycle issues relevant to acquisition cost and customer requirements. This includes a wide range of elements such as non-recurring development costs, recurring production costs (including amortised non-recurring elements), and the recurring operations costs. The paper presents the genetic causal costing approach as a way of achieving the required generic approach.

2.0 INTEGRATED SYSTEMS ENGINEERING

The fundamental activities that describe the systems engineering process have been illustrated by the US Department of Defense[2], as shown in Fig. 2. The customer requirements provide the main input to the systems engineering process, which then feeds into the requirements loop that iterates between requirements analysis, and functional analysis and allocation. The result of the requirements loop is a functional architecture, with identified interfaces between all of the identified performance and other limiting requirements. A supporting systems engineering costing methodology must first be able to operate at this level. The functional architecture then feeds into the design loop which iterates between functional analysis and allocation, and design synthesis. The design loop sees the functional architecture transformed into a physical architecture with concepts being defined along with configuration items, system elements and physical interfaces; and the preferred product and process solutions being selected. Therefore, the systems engineering costing methodology must also be able to operate at this level and preferably, to be recursive in nature for data continuity and to maintain the integrity of the Cost Breakdown Structure (CBS) between levels. Finally, the purpose of systems analysis and control is to provide all of the management activities, and to ensure that there is effective technical analysis and a rigorous basis for the quantitative evaluation of alternatives.

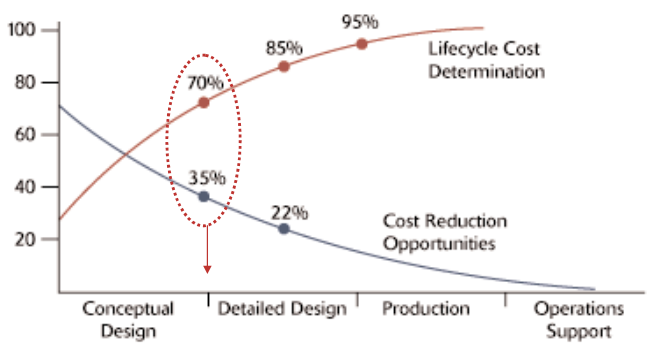


Figure 1. Loss of cost control over the life cycle[16].

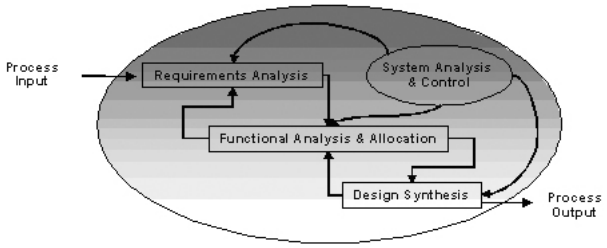


Figure 2. The basic systems engineering approach.

A number of key aspects to systems engineering can be defined from the definitions presented at the outset of the paper, supporting the basic view illustrated in Fig. 2. These aspects then highlight the capabilities which are required to model the process, ultimately providing engineers with tools that can be used to more effectively to implement the systems engineering approach:

- Requirements and functional analysis
- Life cycle analysis and modelling
- Cost analysis and modelling
- Multidisciplinary design synthesis
- Risk and uncertainty modelling
- Concurrent planning and control
- Verification and validation

In addition, industrial practice highlights the need for procedures and tools which help manage all these aspects and their interfaces, ultimately facilitating the verification and validation process.

3.0 COST MODELLING

There are a number of alternative cost modelling methods[5-7] with which one can arrive at a cost estimate associated with any given pursuit. Bottom-up or Detailed Estimating (DE) is the least formulated costing technique and entails the gathering of all cost information that can be directly attributed to the final article, to be cumulated into a highly detailed model. The costs are usually derived from an assessment of material, fabrication, and assembly with additional bought-out and sub-contracted elements. Fundamentally, it is a posthumous approach which is extremely difficult to manage and maintain. Analogous Costing and Case Based Reasoning (AC/CBR) are techniques that principally rely on the similarity and differentiation of like-products to ensure that the cost estimate is comparative to a previous instance. In differentiation, the historical cost from the like-product should be refined or adjusted to account for the variation in product complexities, technical differences or other such factors. This provides a very practical approach but is highly sensitive to change of materials, process, and requirements. An automated form of analogous-type costing uses Neural Networks and Fuzzy Logic (NN/FL) to formulate relations that link independent product-related attributes to the dependant costs under consideration. There are similar weaknesses to the analogous technique plus a requirement for a large population size that is split into input and test groups. Parametric Estimating (PE) typically entails the linking of cost to high-level product parameters through probabilistic analysis in order to establish estimating relations that will combine into a cost estimating model[8-9]. Commercial versions, such as PRICE-H and SEER-DFM, offer a facilitating environment and functionality that allows an organization to calibrate the model with their own historical data in

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order to tailor it to their specific financial needs and business environment. However, as well as historical data, the calibration process requires expert judgment, assumptions and opinion[10-13]. Finally, there are financial accounting techniques, such as Activity Based Costing (ABC), which record the use of resources in determining a more accurate estimate of the total cost, including capital cost rates and overheads.

Elements of all these methods are more or less applicable at various stages of the product life cycle, as illustrated in Table 1. However, it was established in the previous section that ideally, any facilitating costing methodology should be able to operate and interface at various levels and during all stages of the life cycle. This has been a fundamental driver in the development of a generic approach termed Genetic Causal Costing (GCC)[14-18], which is shown in Table 1 to application throughout the life cycle. This is conceptualised in Fig. 3 where the causal definition of the relation of cost to design drivers is seen in the context of product families. The model adopts the scientific principle of categorisation but also incorporates the scientific requirement of utilising causal relations. Essentially, the generic methodology has the following principles:

1. Genetic principle: cost is classified into families according to product and process, to identify likely commonality through shared cost drivers.
2. Causality principle: cost is formulated into a relation as a function of the design attributes which gives rise to a cost potential, using: weights, part counts, sizing, and material selection etc.

The concept of using the causal principle to establish relations with a strong scientific basis is clear, however, not well practiced in cost estimating where statistical significance is often used as the primary requirement. This entails a high degree of risk as there is rarely an attempt to define the range of application of the model or it's sensitively to design and manufacturing change; relative to the historical data used to establish the statistical relation. Causality is a principle which needs to be actively enforced in a discipline that tends to overly rely on isolated statistical data, without the input of engineering know-how based on casual knowledge of the impact of design definition on manufacturability. With regards to the Genetic principle: within aerospace, design tends to be derivative and therefore, the costing blueprint can be seen in previous aircraft. However, new and innovative design, development or manufacturing process improvements may result in significant deviations from the historical precedence, whether reducing cost or time or altering the detailed breakdown proportionality. Engineering manufacturing costs can be classified according to materials, fabrication processes and assembly, while additional costs can be grouped according to support, quality and inspection, and general factory overheads. There is also a large distinction between recurring and non-recurring costs. In terms of production, non-recurring elements include capital equipment such as jigs and tools, while machine costs are amortised over a recuperation period (at a given utilisation factor) and allocated as a resource rate. However, broader life cycle analysis also considers the non-recurring cost of the development process plus additional company recurring overheads, all of which should to be reflected in the acquisition cost. However, the key aspect to this understanding of cost is that it is genetically inherited and that it originates through the engineering design definition, which dictates the materials to be processed and assembled into some product configuration. Environmental factors, such as machining rates and labor rates, can be assumed to fixed at the product definition stage, although logistics and supply chain management introduce a realistic variance.

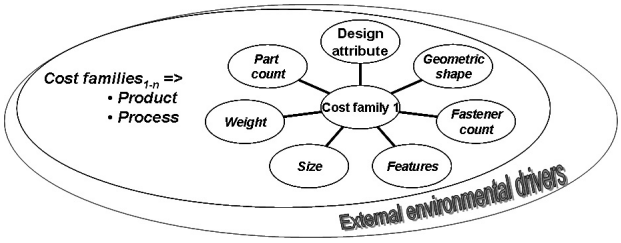


Figure 3. The genetic-causal costing model.

4.0 SYSTEMS ENGINEERING COSTING (SEC)

4.1 Requirements and functional analysis: architecture modelling

The architectural make-up of the system has a direct influence on the emergent behavior that it exhibits. In the case of all architectural modeling for system design, the interactions between components give rise to the 'sum is greater than the whole' property observed in the majority of systems, and in most cases, it is this emergence which is designed for. On the hand, however, this emergence may also manifest itself in undesirable behaviour (so called side-effects), leading to a need to establish methodology which will effectively identify, and eventually control and drive system development to produce more cost effective, stable system designs, with instances of redesign due to unanticipated emergent behaviour limited.

Many of the interactional features of system design are clearly and easily identifiable through established systems engineering procedures — interactions between physically linked systems tend to be obvious, and functional interface identification using methods such as N2 diagrams are proven[2]. However, there is still the issue of identification of technically induced interfaces, which may promote data exchange between physically remote systems[19], which precludes the use of many of the traditional systems engineering tools.

In order to address this issue, Price *et al* (2005)[20] introduced the concept of a system technical architecture, an additional view of the system in which the technical linkages induced by system analysis through the design phases could be identified, and the effect of

Table 1
Matrix of cost estimating techniques and application to systems engineering stages

	Techniques:					
Life cycle phase:	DE	AC/CBR	NN/FL	PE	ABC	GCC
Concept and technical development	✔	✔		✔		✔
System development and demo	✔	✔	✔	✔	✔	✔
Production and acquisition	✔	✔	✔	✔	✔	✔
Operations and disposal				✔		✔

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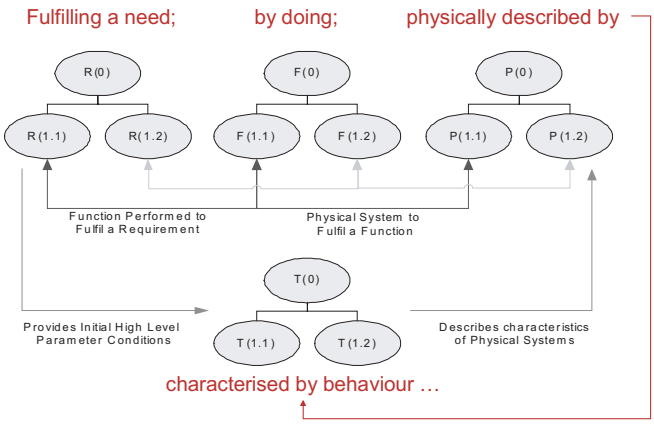


Figure 4. Relationship of RFP architectures to the 'Technical' architecture.

modifications on design then reflected into the more traditionally held requirements, functional and physical architectures. Initial consideration of system requirements gives rise to a series of high level design characteristics, which form the initial high level parameter definitions for system design (so-called independent design parameters, as they have no ancestry within the system architecture). Through a series of operations on these parametric sets, a series of dependent parameter sets are introduced (for which a clear set of parent elements may be determined). These independent and dependent parameter sets provide the technical definition of the system components contained within the system architecture. By constructing the architecture in this manner, a clear and traceable pathway through the design process is developed, which supports the additional architectural models, with a clear linkages between each, as shown in Fig. 4. The illustration also highlights the key components being addressed through fulfilling a need (requirements analysis), by the product doing certain things the customer wants (functional analysis), by a physically defined design (physical analysis), that is characterised by certain behavior (technical analysis). The addition of the latter technical architecture to the accepted requirements, functional and physical (RFP) architectures is an important contribution in that it highlights the challenge of integrated modeling of the RFP to quantitatively facilitate the systems engineering approach.

For high value products, the cost associated with system design, development and operation is of extreme importance, and is often a driving factor behind the system design. In many instances, high value products require a large upfront investment, after which it can be several years before a return is realised by the customer (as is the case in the commercial aircraft industry). In order to counteract this, robust methods of optimising system design for cost need to be made available, with the potential for modification of the objective function of the costing analysis in order to react to the customer needs. If the customer objective function for cost optimisation is the overall reduction of weight and the associated fuel consumption over the system lifecycle, costing analysis will identify those parameters which influence this and highlight recommendations for system optimisation. However, the overall implication of the modification of design parameters is often far reaching, and is not immediately obvious within the localised system component being considered. By then integrating the cost modeling into a design framework, these recommendations can be reflected in the global system model. By considering the cost optimisation as a component of a global framework, it is then possible to not only optimise according to customer requirements, but also to assess the global effect on all associated disciplinary analyses throughout the overall system design.

The advantages of a holistic system view are multiple — localised optimisation may be translated into the global model, so that the computational intensity of optimisation routines may be reduced (full-scale modeling is not required) while still maintaining an awareness of the system components which are affected. The objective function for optimisation may also be modified and direct comparisons of the affect on the global system design easily reflected, to enable the best-fit system to be achieved.

4.2 Cost modelling

Figure 5 illustrates the conceptual model of how cost analysis and control can be integrated into the systems engineering methodology. The product life cycle is broken down into four main phases, with major milestones associated with the passing from one stage to the next. For example, the major milestone or exit criteria from the concept and technology development phase is the full definition of the system level architecture, which is subsequently transformed into a functional and then physical architecture during the system development and demonstration phase. It can be seen that the core activities of systems engineering, as shown in Fig. 5, are applied sequentially during each phase of the life cycle. In addition, the costing that occurs during the design phase is illustrated as a top down process that matures in complexity and fidelity as the design definition becomes fully complete at the Critical Design Review (CDR). The design phase is also associated with a flow-down of the requirements that are then allocated within the functional architecture. Subsequent to the CDR, the verification phase is illustrated as a bottom-up process were parts and components are fabricated and integrated into assemblies and sub-systems that ultimately, are tested, verified and validated at an operational systems level. Figure 6 is important as it illustrates the need for a more holistic approach to the cost modeling of acquisition cost while also highlighting some key desirable characteristics regarding the accommodation of:

- the recursive top-down environment within which it operates, when estimating costs
- the transformation from a system requirements level, to a functional level, to a physical architecture and definition
- the systems application being time dependant and requiring an iterative, sequential approach
- the need for verification and validation following the design phase (estimate) costing

4.3 Multidisciplinary design synthesis: model integration

The systems engineering framework provides for a breakdown of the aircraft into more manageable sub-systems. This breakdown is based on the physical architecture which is ultimately derived from functional requirements based on customer requirements, as illustrated in Figs 2 and 5. The process is constantly iterating with design synthesis continually contributing to the assessment of the system performance. Unfortunately the models used in design synthesis are multi-disciplinary and depending on the level of detail known about the design and accuracy of answers needed have different fidelities. To compound this, the design models often cut across system boundaries since the design models are usually based on the physical inception of the system. For example the master loads model is usually and idealised finite element model of the major airframe structures and is drawn on for design and analysis data for many other systems, such as the nacelle, when and where appropriate. The local behavior of any component or sub-system may require a local analysis for a small number of key variables based on one or two key disciplines. However, to facilitate trade-offs at the higher levels this information needs to be available to inform the trade-off analyses[19]. To achieve this, local detailed models must coexist with high level idealised models and these must be accessible across systems as well. Geometry focused approaches which reflect the systems

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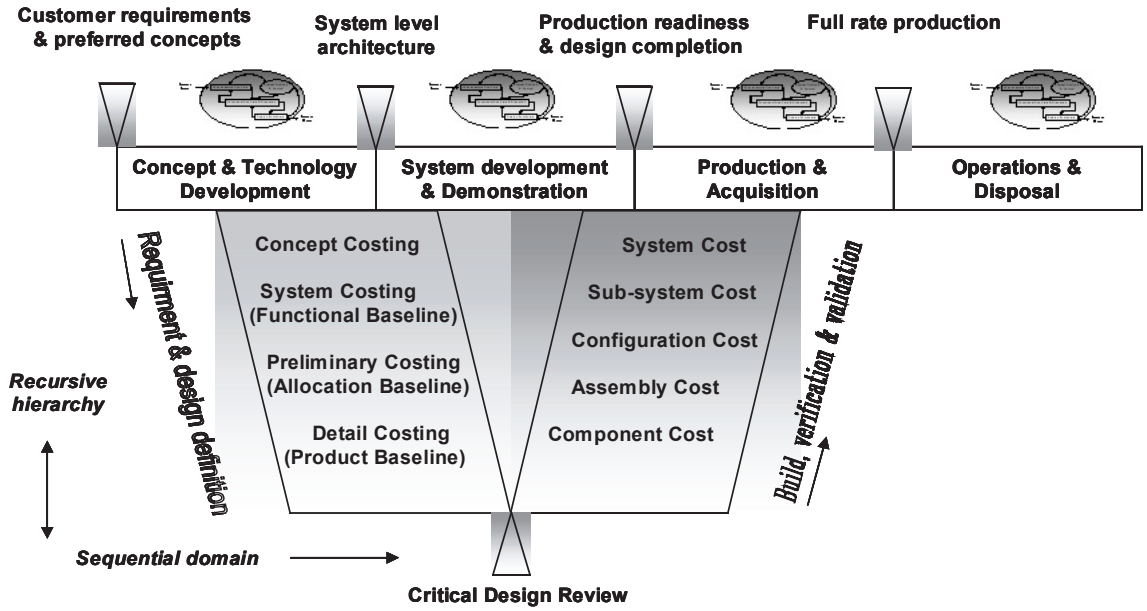


Figure 5. Integration of cost modelling into the systems engineering life cycle paradigm.

engineering framework have been proposed[20-23] to facilitate this feed of data through the levels and across the systems, enabling systems sensitivities[24] and performance to be measured more reliably.

Figure 6 illustrates the multi-level, multi-fidelity framework being developed to achieve design synthesis. On the left-hand side of the figure the aircraft structural design is first assessed through a simple frame analysis, which then is used to develop solid models to represent a more realistic geometric definition. The solid models can then be used to carry out more accurate analysis of structural integrity and cost etc, to be feed iteratively into the sizing procedure. Further levels of abstraction can be imposed down to localised detailed modeling, depending on the maturity of the design process in the development stages following the process illustrated in Fig. 5. On the right-hand side of Fig. 6 the integration of systems engineering costing is illustrated with fidelity, discipline and time dimensions. This relates directly to the need for the additional technical architecture presented in Fig. 4 as the integration of quantitative modeling, e.g. for cost in this case, requires that multi-fidelity cost models are required to facilitate the systems engineering approach in order to enable the coupling to the other multi-fidelity models that characterise the multidisciplinary system design space. This is an important issue since the majority of finance models that are used in industry are usually built relative to organisational financial reporting criteria rather than life cycle systems monitoring and control requirements.

4.4 Risk management: uncertainty and sensitivity modelling

The assessment of risk within the global system design is a major component of the system synthesis loop, with risk assessment performed at each stage within the design process illustrated in Fig. 5. As the design evolves, the system interactions increase in complexity, with multiple interactions occurring over multiple interfaces rather than over a few well defined points. In order to reduce the risk of instances of unanticipated emergent behaviour, the system technical architecture reinforces the traditional system interface management methodologies in order to limit the number of undefined architectural interactions. As all interactions are characterised by a transfer of data across component boundaries, the assessment of technical interactions enables this to be achieved in an effective manner. For example, part of the technical architecture for an aircraft would include a structural model and a manufacturing model that also predicts cost. The potential for an interaction will be highlighted at any point where each of the models share or pass data; this being viewed as one definition of an interactive relation. Consequently, a specific example of an interaction is given by the desire to reduce stringer pitch in order to reduce skin thickness and overall weight, which however, has a negative affect on manufacturability and cost due to the increased effort in fuselage panel assembly[15].

If a component is altered within the system overall architecture, it has the potential to affect every other component within the system due to the hierarchical nature of system design. This impact on the system design is characterised by the behaviours that are exhibited by the system. In many cases, minor modifications to system design will have no impact on the operation of the global system, and as such may be implemented without risk. For most components within the system architecture, there is an identifiable design space, which is determined by the boundary conditions placed upon each system component. Each system component contributes to a series of relationships. Each of these relationships has constraints placed upon it in the form of technical requirements. By identifying each relationship that a component contributes to, each set of the bounding conditions can then also be identified, and the design space constrained accordingly. By approaching the design in this manner, a constrained design space for each system component can be identified at a very early stage within the design process, while increasing confidence in the stability of the system design.

A generic description of the system design space constraint is that for every parameter x, which has a set of properties $p(x)$ such that $x = <x, p(x)>$ for every relationship F_N (where $F_N = F_1, F_2 \ldots F_N$) that x contributes to, there are $2N$ identifiable constraints, leading to the creation of an N-dimension design space for that variable. By including an uncertainty factor δ to each of these constraints, the uncertainty within the constraints may also be accounted for. For the example shown in Fig. 7, a cost parameter x is constrained by five different relationships that where identified in the process illustrated in Fig. 4. Each of these relationships provides an upper and lower

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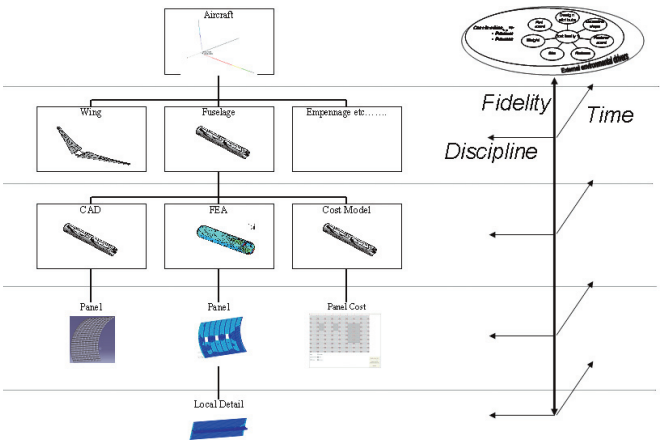


Figure 6. Integrating disciplines that drive design at various levels of definition.

allowable boundary in each of five different axes (the conditions have been projected into 2D). By adding an additional condition δ to each of the boundaries, the design space is further reduced, in order to address the issue of uncertainty within the constraints. Such an analysis uses the cost modelling established, for example, illustrated in Fig. 8. It is also evident from Fig. 7 that the uncertainty can be taken from the variance recorded from production analysis, or can be imposed at certain levels in order to loosen the constraints to let the procedure identify a more optimal global solution. In the context of risk being defined as probability and consequence, the uncertainty factor δ is incorporating a probable range of variance into the calculations that generates a more realistic spread of expected values, which can then be subsequently used to provide a more robust risk assessment of design consequence.

4.5 Cost management: generic modelling

The systems engineering methodology of Fig. 5 presented a life cycle balanced view of the integration of cost into the process of meeting customer requirements through a verified and validated design synthesis. This balance within the design process is achieved if feedback is incorporated, e.g. from the operations stage back into the design stage; exemplified in the work presented through considerations of fuel burn and maintenance costs. This section addresses costing issues from all of the key stages within the life cycle and takes a more detailed look at the modelling capabilities required to facilitate a life cycle balanced design process.

4.5.1 Development cost

The systems engineering process detailed in Fig. 5 began with concept and technology development. The associated cost is largely treated as a non-recurring element, i.e. a one-off effort that is not repeated, although in practice design modification does occur during the production stage as the manufacturability of the design solution becomes evident, and later at the operations stage through modifications and upgrades. However, concurrent development effort, through the application of design for manufacture and design for Six Sigma approaches *etc*, is increasingly being imposed in an effort to reduce this posthumous design effort. Figure 8 presents some data relating to the non-recurring design effort recorded for fuselage sections. The design hours, as the dependant variable, are being modeled as a function of both part count and weight. It is highlighted that there is a minimal 15% delta in the cost being predicted depending on the independent variable. In terms of the genetic-causal approach, design cost is identified as a cost family or category while the independent variables should be of a causal nature. It is well known that weight is a good indicator of cost and is often used in parametric cost analysis[25]. However, it is recommended that part count also be considered as a more causal driver, although there is a major distinction between certain structures depending on whether they are metal or composite; composites being more likely to result in part reduction through having moved effort from the final assembly stage to the lay-up stage (a type of pre-assembly assembly). Notwithstanding, weight is more loosely coupled to cost in the fact that 'more stuff is likely to cost more', i.e. more material requiring more design effort in order to define it. However, in this instance part count, even with a slightly lower statistical significance (R^2 = 0·92 as apposed to R^2 = 0·93 with weight as the independent variable), is assessed to be more causal as it relates directly to the number of drawings to be generated to define the assembly configuration. It is evident that for the small amount of data shown, these high level cost drivers can be used in the assessment of the devel-

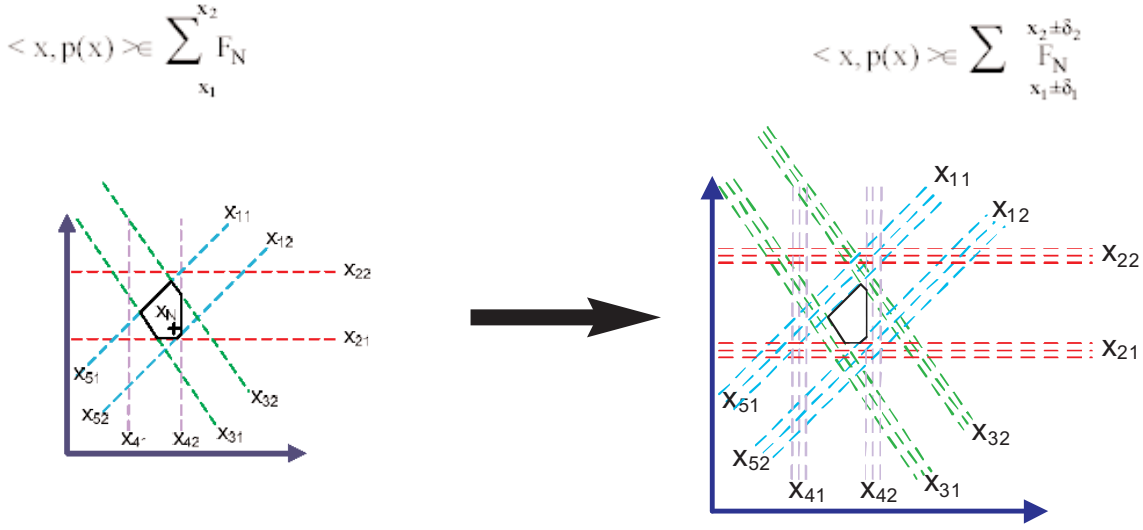


Figure 7. Multi-cost constraints fuzzified through uncertainty of parameter impact constraints.

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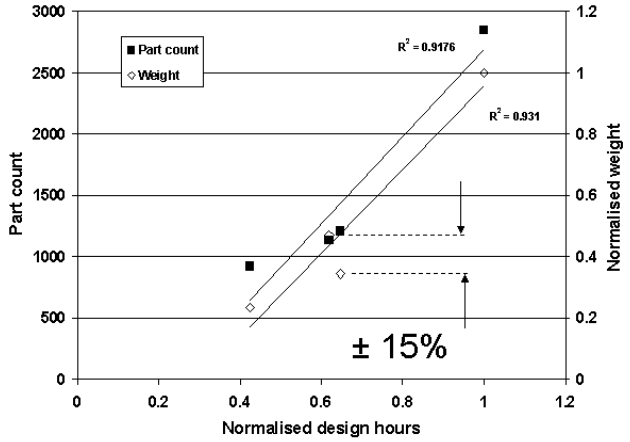


Figure 8. Cost modelling of design using high level cost drivers.

opment cost associated with the design hours expended. Weight can be used at a very early stage, when weight has already been estimated, while part count can then be introduced when that is known, if only to give a second estimate.

4.5.2 Production cost: in-house

The next stages detailed in Fig. 5 are the systems development and production. Both these stages require the use of production cost modelling in order to more accurately access the recurring and non-recurring costs associated with manufacturing the design which will be frozen at the Critical Design Review (CDR). This section addresses the cost modelling of in-house production costs while the following Section addresses procured production.

Following the genetic-causal principle, cost is first disaggregated into families according to material, treatments, fabrication, and assembly; each of these can be further broken down as required. Then causal drivers for each of these are identified and formulated into a relation that can be developed using either statistical or generative modelling. The plots to the left on Fig. 9 show the make cost (fabrication) being related simply to stringer length, for a particular family of stringers, whether T, Z, L Section etc. The regression analysis of the data requires both a constant and a slope in order to characterize the relation to some linear approximation, shown in the upper and lower graphs respectively. Subsequently, the distributions (uncertainty characterisation) for these statistical components can be utilized through Monte Carlo analysis in order to model the likely variation in cost due to the variance observed (or imposed relative to some criteria), thereby producing a more robust cost estimate. This is illustrated to the right where both distributions have been used by the Monte Carlo analysis to provide the rigorous assessment of the likely distribution of cost.

4.5.3 Production cost: procurement

The second category within production costs is the procured items. Currently, 70-80% of parts are procured from the supply chain, even including made sub-assemblies, in an effort to streamline production effort and engage the most cost effective producer. Procurement cost modelling is characterised by the analysis of large data banks of part prices and often only very basic information regarding the manufacture, that being too sensitive or proprietary in the opinion of the supplier. Figure 10 shows a typical breakdown of the procured spend at Bombardier Aerospace Belfast, representing an annual spend of some US$600m for 50,000 unique parts. The genetic-causal principle is imposed to breakdown the database into a hierarchy of part families, using attributes to improve the fidelity of the grouping technology imposed. Subsequently, the causal principle is imposed in order to develop costing relations that predict procured cost relative to known variables. The variance is typically much greater than for in-house production because there is a strong market influence, i.e. the supplier selling the parts for the highest price possible rather than by the cost-plus-profit model, or sharing risk and selling at lower prices in order to win the work.

Figure 11 shows some results obtained from various techniques of linking the procured cost for the causal drivers identified, using both regression analysis and neural networks to develop the formulation. The group number relates to a division of categorisation levels within Fig. 10, for example group 1 relating to distinction made at a high level only in terms of commodity, e.g. machining or sheet metal, while group 7 refers to a much more detailed grouping relative to part and process attributes. The RMSE value shown can be interpreted as the non-dimensional error, where group numbers or levels 6 and 7 represent the much small data bins for a particular part family, machined bulkheads in this case. Group 5 analysis is returning an accuracy level of approximately 5-10% for all the parts considered in that larger bin, while groups 6 and 7 show that machined bulkheads are not a particularly well modeled sub-

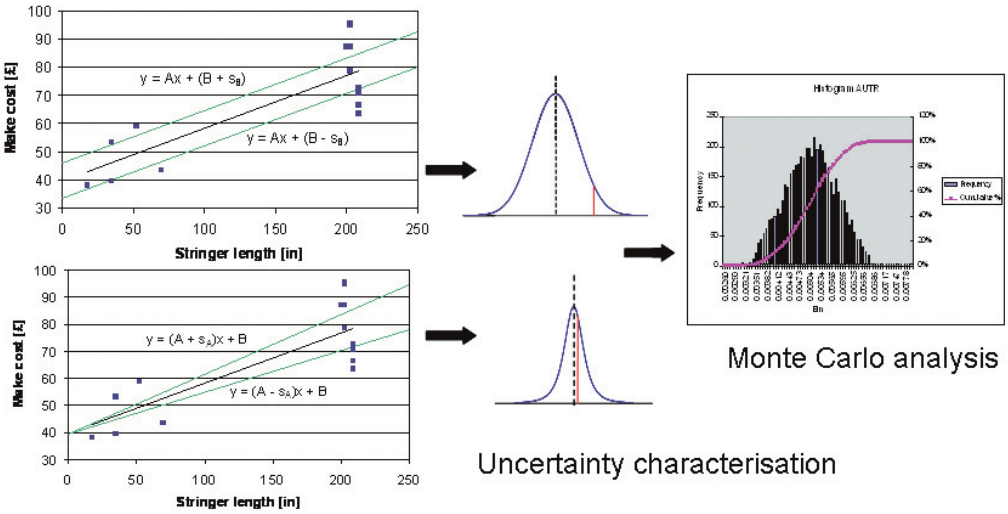


Figure 9. Production cost modelling and decomposition with applied uncertainty analysis.

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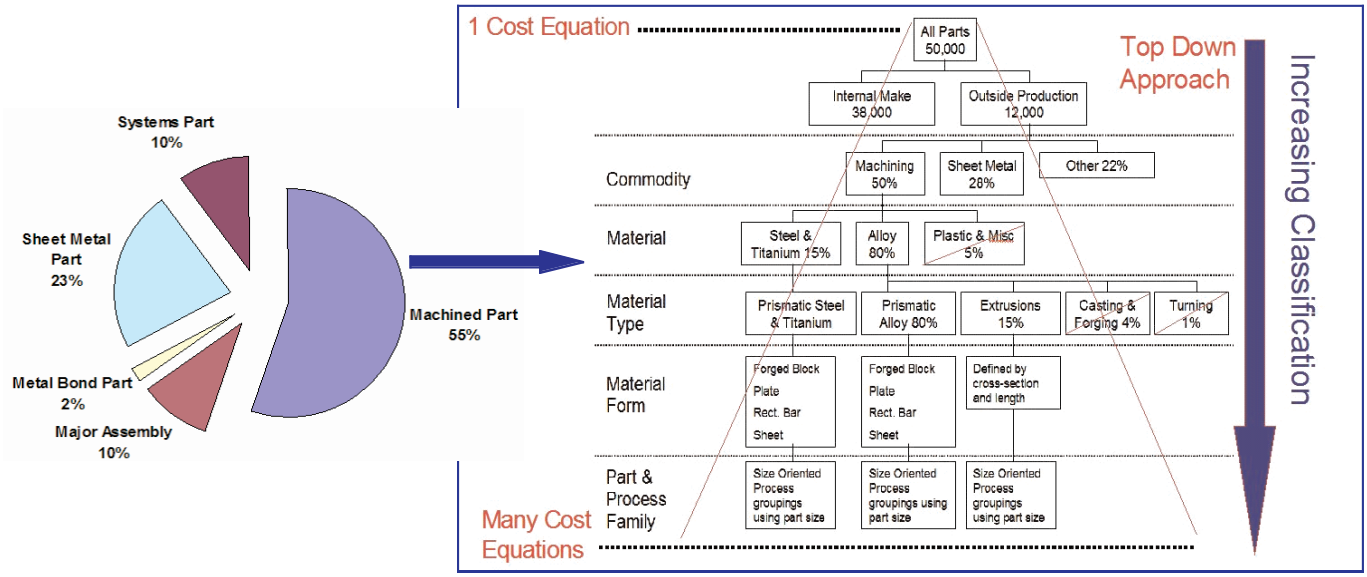


Figure 10. Procurement cost analysis and modelling through genetic cost decomposition.

category. The poor accuracy is due in this case to the lack of design instances and to the wide variation in design definition, relative to the bulk of parts considered in group 5.

4.5.4 Maintenance cost

The following section deals with the overall cost of operations but this section will consider maintenance cost in particular. A breakdown[26] of direct maintenance costs for Delta Airlines and American Airlines is shown in Fig. 12.

It can be seen that these airlines commit approximately one third of the direct maintenance cost in it's own maintenance labour efforts, one third in materials (including spares that are also supplier to third party maintenance contractors), and one third to the cost incurred through third party contractors (one third being apportioned to airframe costs and two thirds to engine cost). In addition, RAND[27] have estimated that 34% of the overall direct maintenance costs can be attributed to airframe maintenance, 27% to engine maintenance, and an additional 39% in associated maintenance burden.

Investigations were carried out in conjunction with Shannon Aerospace, who is a third party maintenance contractor. The company carries out full maintenance on a wide range of aircraft, including Boeing, McDonnell-Douglas and Airbus aircraft. The maintenance includes routine C-checks, more detailed C-checks and full D-checks, which are scheduled into a cycle that is repeated throughout the aircraft's life. For example, a full D-check demarcates the end of a cycle of approximately eight years, and is required to occur at a given frequency throughout the life of the aircraft in order to safely assess crucial fatigue and crack growth issues, etc. The more detailed C-checks typically occur every 16 months, while the routine C-checks can be carried out every one or two months, typically every two months for Shannon. There is also an indirect cost in terms of the loss of income and therefore, a larger time interval reduces the loss in income, also with regards to the out of service time incurred before and after the actual maintenance time, e.g. transportation, preparation and waiting time.

A cost model was developed from the Shannon Aerospace data in order to estimate the labour associated with their airframe maintenance. The labour for the maintenance cycle mentioned is accumulated from an equation that has a factor to account for different types and sizes of aircraft, and another factor to estimate the cost of basic materials; whereas aircraft spares are supplied directly to the third party from the aircraft producer but paid for by the airline, i.e. are not included in the materials cost of the third party. The basic method utilised by the model can be summarised by considering the equation below, including the cumulative labour associated with the scheduling of the three checks ($L_{routine\text{-}check}$, $L_{C\text{-}check}$, $L_{D\text{-}check}$), a labour rate for the company (R_{labour}), a factor for basic materials ($F_{materials}$) and if useful, a factor to scale up to estimated total direct maintenance ($F_{scale\text{-}up}$).

$$C_{Maintenance_cycle} = F_{scale\text{-}up} F_{materials} R_{labour} \left(\Sigma L_{routine\text{-}check} + \Sigma L_{C\text{-}check} + L_{D\text{-}check} \right)$$

where the cumulative number of routine checks associated with $L_{routine\text{-}check}$ is determined by the time intervals I between the various checks:

$$\left(\left(\frac{I_{C-check}}{I_{routine-check}} \right) - 1 \right) \left(\frac{I_{D-check}}{I_{C-check}} \right)$$

while the number of C-checks associated with $L_{C\text{-}check}$ is similarly determined from:

$$\left(\frac{I_{D-check}}{I_{C-check}} \right) - 1 .$$

A comparison of the results from the maintenance model are compared in Fig. 13 for narrow-body aircraft in the size ranges of 1) 80,000-12,000lb, 2) 120,000-150,000lb and 3) 150,000-280,000lb; and wide-body aircraft in the 150,000-280,000lb range. The estimated labour hours are presented for each of the six main phases that contribute to a full maintenance cycle, phases 1-5 consisting of a number of routine C-checks followed by a more detailed C-check or a full D-check for phase 6. It can be seen that the model is most accurate for the smaller narrow-body aircraft while the larger wide-body and narrow body aircraft are less accurate due to the variation in the labour associated with the more detailed C-checks carried out at the end of each phase in the maintenance cycle. However, the error in the total maintenance cost for the cycle was very low: narrow-body 1 and narrow-body 2 being +0·2%, narrow-body 3 being –1·1%, and wide-body 3 being +0·7%. The highest individual error of 20·8% occurred for phase 1 of the wide-body aircraft, while the average error for each of the associated phases was 16%. However, the error is smoothed out when considered cumulatively over the full cycle, due to the balancing of under and over estimating.

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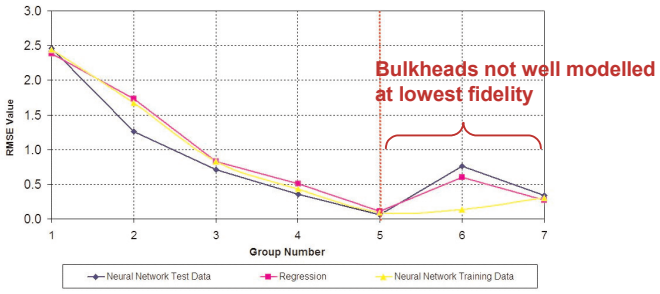


Figure 11. Prediction error for procured cost based on neural net and regression techniques.

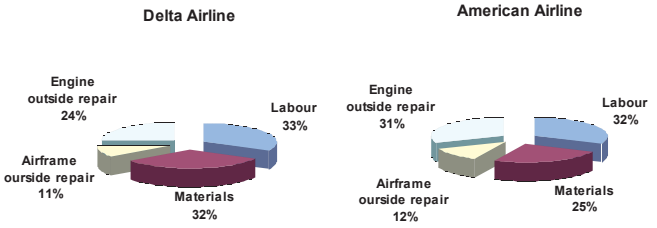


Figure 12. Breakdown of total direct maintenance cost for Delta Airline and American Airline (Unisys, 2004).

In the context of the Systems Engineering Costing (SEC) methodology presented in this work, the model can be used early in the development phase to estimate the impact of design and manufacturing decisions on the maintainability of the aircraft. In particular, the model considers three types of maintenance checks for four groups of aircraft according to size and configuration (narrow-body and wide-body). Therefore, the impact of the design or manufacturing decisions is linked to the type of check when it would be considered, therefore increasing the accuracy of the assessment during development. This would be relevant to type of maintenance associated with a particular part's design, for example, primary fatigue and crack issues being estimated relative to the labour value attributed to the full D-Check. Therefore, the modeling can be used in the context of Systems Engineering Costing (SEC) to facilitate a life-cycle balanced analysis of the product's cost that can be used early in the development cycle (see Fig. 5) to produce a more competitive product for the customer.

4.5.5 Operations cost

The final stage considered in Fig. 5 is the operations cost, which represents the aggregation of all acquisition costs detailed in the previous sections, in addition to all the other operational cost categories identified. Figure 14 presents a pie chart detailing the proportional contribution, with ownership being the financing of the acquisition cost at 54%. The engineering effort expending in the early development stages influences ownership, maintenance (13%) and fuel costs (15%), while crew (13%), landing fees (2%) and insurance (3%) are largely independent. It is striking that the chart supports the view that more effort is required in reducing acquisition cost as it has over three times the influence of performance (fuel burn). In this context, the cost impact of trading-off aerodynamic tolerances and manufacturing tolerances, with respect to direct operating cost, was the focus of some of the earliest cost modelling work carried out at QUB[28].

The detailed modelling presented in the previous sections can be incorporated into the design synthesis effort in order to drive the design definition relative to manufacturing cost as well as just performance considerations, the later being the more typical

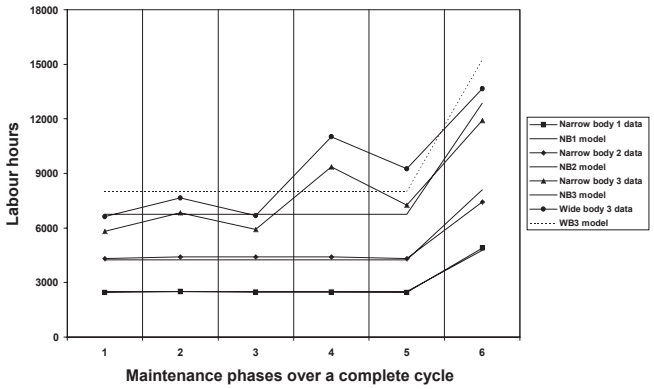


Figure 13. Comparison of model predictions relative to industry data for a complete maintenance cycle broken up into 6 phases.

approach taken. Consequently, the variables which drive manufacturing cost are coupled to the variables which drive design definition and therefore, the design process can be optimised relative to some objective criteria. Figure 15 presents the results of such an optimisation analysis for a fuselage panel pictured on the left. The impact of manufacturing cost on DOC as an optimisation criterion is highlighted, as well as the significant change in the design solution; with wider stringer pitch, heavier stringer design and thicker skin thickness. The cost is being assessed in terms of the reduction in operating cost (US$/m^2 of panel) from some baseline design position, where the optimisation criteria is either minimising weight (W), material cost (mat), manufacturing cost (mfc) or operating cost (doc). It is not surprising that minimal material cost is not a good criterion for reducing operating cost while operating cost is some 20% better than both weight and manufacturing cost. The parity between weight and manufacturing cost is further evidence of the importance of manufacturing cost, whose inclusion into the operating cost is what is giving the increased saving over the minimal weight criteria.

4.6 Planning and scheduling: digital manufacture

An important output from the system engineering process is detailed planning and scheduling information required for efficient production. Digital manufacturing tools can be used in this regard to link the design Bill of Material (e-BOM) to the manufacturing BOM (m-BOM), with each being regarded as different views of the one BOM, thereby reducing the cost of consolidation currently required

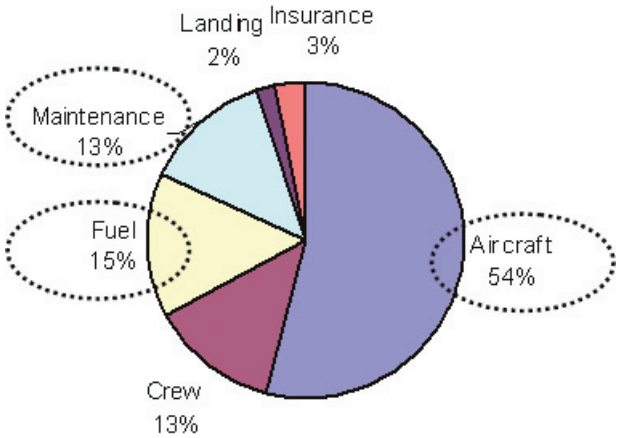


Figure 14. Typical breakdown of operating cost for a regional jet.

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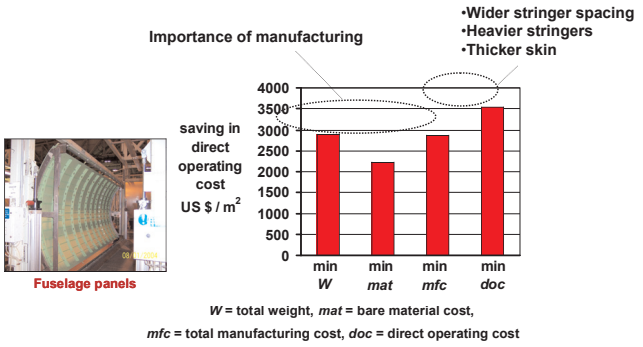


Figure 15. Modelling operating costs according to various optimisation criteria.

with separate design and manufacturing data systems, and the associated likelihood of potential errors. The manufacturing BOM can then be indented and configured into a hierarchical Work Breakdown Structure (WBS) which then can be used to formulate network planning in order to optimise the work flow. Key products of this process are the Integrated Master Plan (IMP) and Integrated Master Schedule (IMS), which are used to manage this effort.

Figure 16 illustrates the type of outputs from a digital manufacturing tool. A Product-Process-Resource (PPR) hub is used at the heart of the system to integrate the design BOM with the manufacturing BOM, the parts being attributed with additional manufacturing and cost information at that stage. The assembly process is then defined as consisting of some combination of a number of operations with associated precedence, time and cost. The network analysis can then be carried out to determine the optimal detailed work flow, thereby fully defining the most cost effective solution to each task identified in the Integrated Master Plan.

4.7 Verification and validation: simulation modelling

A substantial amount of verification has already been presented in the cost management section, including comparisons of data and predictions for development, production, procured, maintenance and operations costs. However, Fig. 5 referred to the verification and validation process that occurs during production and acquisition, subsequent to the Critical Design Review (CDR). This process is crucial to any company improving its business and can be used to review and modify the design under consideration and its manufacture. However, design modification is a very expensive

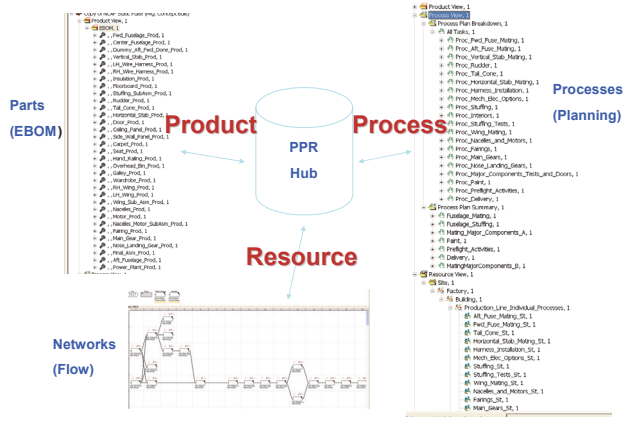


Figure 16. Integrating design definition with manufacturing planning and scheduling.

procedure, especially due to the aircraft certification procedure. Also, such information could be used at a much earlier stage to find a more optimal solution in a less constrained design space, as illustrated through Fig. 7. This is made possible through manufacturing simulation, which allows detailed manufacturing processes to be accurately modelled and integrated into the early development processes and thereby providing a virtual verification and validation capability. Although true verification and validation process will not be complete until production is completed, the manufacturing simulation is linking the value of that process back into the design currently being developed, thereby reducing its cost through design and manufacturing optimisation. Similarly, true verification and validation must be associated with feedback from the operation and in-service demonstration, if whole life cycle balanced is considered. The simulation work presented in this section could be used to model maintenance effort but the bulk of such a verification and validation process would be the updating and refinement of life cycle design tools for use on subsequent products and contracts.

Figure 17 illustrates the modelling definition encapsulated in manufacturing simulation tools, also illustrating the BOM information being stored under the geometric definition, linking to the digital manufacturing capabilities discussed in the previous Section and illustrated in Fig. 16. The constituents BOM parts are all modeled relative to the jigs and tools, for a fuselage panel shown to the left while the full fuselage barrel section is shown to the right in its final assembly jig.

The actual simulations are then carried out in order to optimise relative to criteria such as cycle time, operator efficiency, or overall assembly cost minimisation. For example, Fig. 18 shows plots of the process and operator efficiencies (left and right graphs respectively) simulated for the fuselage section shown in Fig. 17; fitting shown to be higher than riveting in the plots. Relative to the criteria mentioned, the process efficiency plots to the left are more associated with the minimisation of cycle time while the operator plots to the right are associated with the minimisation of cost; depending on the goal of the optimisation. It is highlighted that the utilisation improvement is resulting in more steady and efficient labour deployment. It can be seen from the process plots to the left in Fig. 18 that the two processes represented, fitting and riveting, are being used at much more stable and constant utilisation rates. This concurrent planning thereby reduces cycle time and maximises the effective utilisation of labour. The plots to the right hand side highlight the latter point where it can be seen that the fitting and riveting processes required a more constant number of operators after the optimisation. The stepping in the upper plot signifies varying numbers of operators throughout the assembly process, who can not be redeployed in the short terms and therefore are frequently idle, reducing the process efficiency. The improvement illustrated resulted in a 20% reduction in the assembly cost, within the designated cycle time constraints for required throughput.

Finally, Fig. 19 presents some more validation data relating to overall unit price. The data has been gathered from redesign efforts and is significant in showing the linkage between unit cost reduction and part count reduction. At a detailed level, this validates the DFM methodology[29,30] of reduced part count, where the reduction in

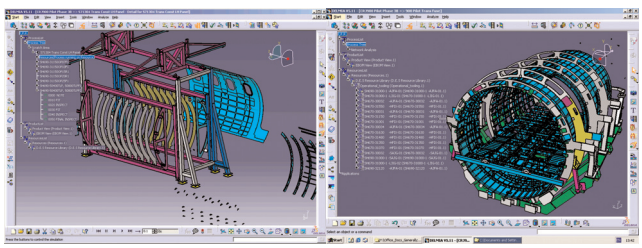


Figure 17. Simulated modelling of the production process in virtual reality.

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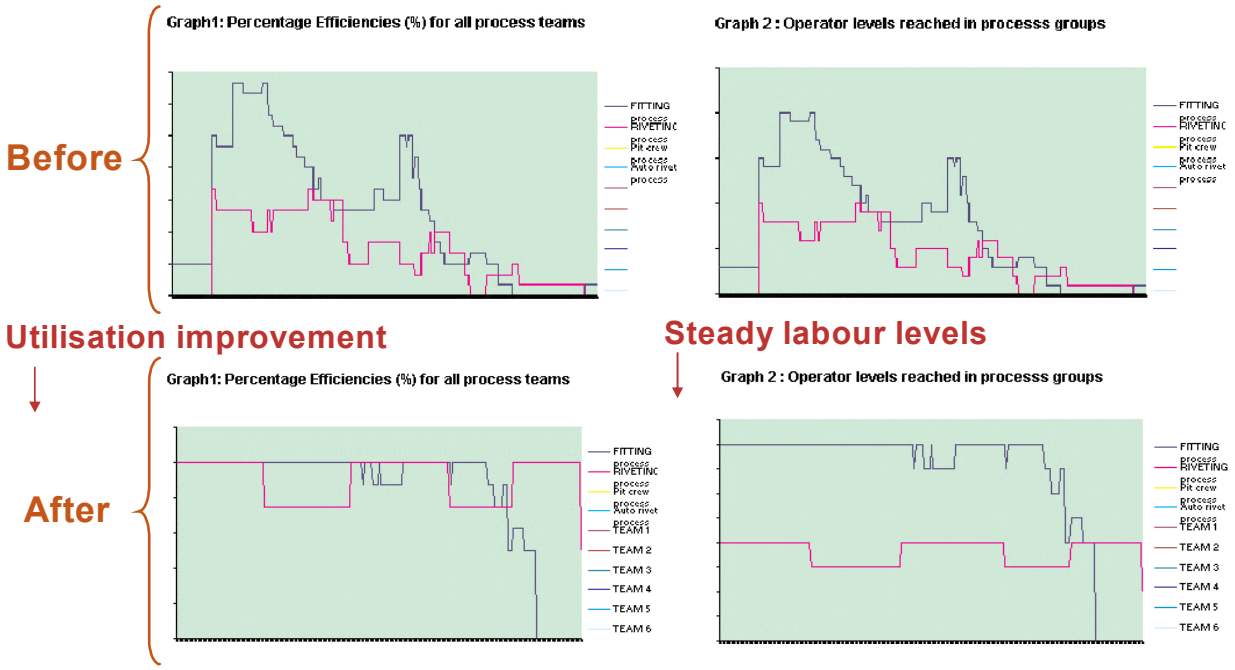


Figure 18. Simulation as a tool for verification of optimal manufacturing solutions.

assembly effort is enabled through the cost effective exploitation of complex part fabrication. However, at a higher level, the results validate the integration of manufacturing and costing into the Systems Engineering process in order to produce more competitive products that meet customer requirement in terms of cost as well as specification and performance. However, as detailed in the operations and maintenance sections, it is crucial to also incorporate in-service costs in order to have a life cycle balanced approach, specifically factoring in the contribution made from each of the stages relative to what the original customer requirement for the product-in-use is.

5.0 CONCLUSIONS

The paper has presented a methodology for the life cycle integration of cost into the systems engineering approach, termed Systems Engineering Costing (SEC). This has included an assessment of cost modelling technology, and the application of cost modelling to a number of key tenants of systems engineering, including: requirements and functional analysis; life cycle analysis; multidisciplinary design synthesis; risk management; cost management; planning and scheduling; and verification and validation. Cost management components were disaggregated according to the development stage, production stage (including in-house and procured), and maintenance and operations stage. The integration of cost into SEC has been facilitated by the genetic-causal costing model and ultimately, it has been shown that the principles have been used in the development of engineering-oriented cost models for each of the key stages through-out the life cycle of commercial products (upgrade being a key feature of defence life cycle analysis). The key principles of cost categorisation and causality were highlighted as the fundamental tenants of the genetic-causal modelling approach. Therefore, it is concluded that the systems engineering approach offers a facilitating framework for the effective integration of cost into the life cycle balanced design of aircraft, including development, in-house manufacture, procurement, operation and maintenance. Currently, the work has being developed into a methodology that can be used in the context of a systems engineering approach to integrated aerospace design and technologies. It is being applied on an individual basis through research with a wide number of industrial collaborators but has not been validated as an integrated approach through an integrated case study, that constituting a much more ambitious validation procedure.

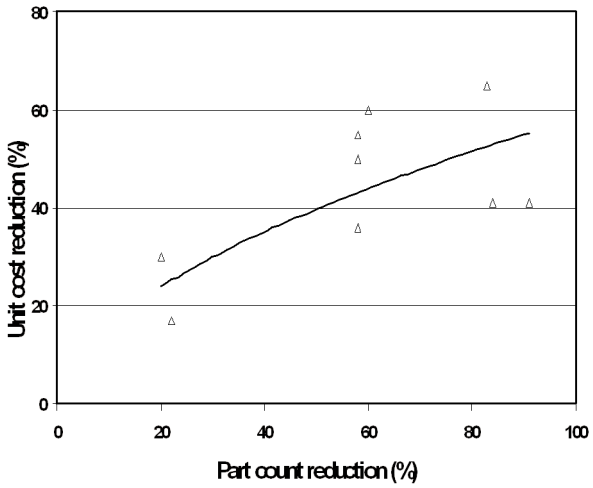


Figure 19. Cost integration validated in SEC approach as cost reduction is evident through life cycle design synthesis.

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