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Predicting Foreseeable Uncertainty Using a Value Driven Design Methodology

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Program overruns and delays have long been an issue within the aerospace industry. With so many external pressures from stakeholders and the continuously declining economy, aerospace manufacturers and developers are forced to concentrate effort to limit these overruns and delays. This paper introduces the development of a Value Driven Design inspired Capability Function (CF) that will ultimately be used to predict overrun and delay occurrence while also quantifying their economic impact on the program being developed. Within this paper specifically the inherent sub-variable reactions within the CF are explored and the most influential and design controllable variables identified. Upon identifying these variables an updated approximation of the CF is presented.

Keywords: Systems Engineering, Value-Driven Design, Cost, Uncertainty

Nomenclature

C_{DC} = Cost of delay and cancellation (of flight)
C_{Dev} = Cost of development
C_{Dis} = Cost of disposal
C_{Man} = Cost of Manufacture
C_{PF} = Cost per flight
$Disc_C$ = Customers discount factor
$Disc_P$ = Producers discount factor
E_{TPF} = Externality tax per flight
F_{Dcomp} = Uncertainty factor for design complexity
F_{Din} = Uncertainty factor for insufficient design
F_{Dr} = Uncertainty factor for design reliability
F_{PM} = Uncertainty factor for project management
F_{SC} = Uncertainty factor for supplier and contractors
F_{UC} = Uncertainty factor for uncontrollable uncertainties
MS = Market size
R_{PF} = Revenue per flight
UF = Uncertainty Factor
U_Z = Utilisation

I. Introduction

In a progressive world where technology is advancing rapidly, developing and producing new products has become a more complex process. Fuelling this advancement are groups of diverse stakeholders and customers all looking for the most robust product at the most competitive price.

When the current economic volatility is also considered the task of developing and producing a new product becomes a minefield of potential failure. With so many conditions to satisfy, the role of the designer has not

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only become more important but has become a role of greater responsibility. The success or failure of a product or program is now seen to rely predominately, if not solely on the decisions of designers as pointed to in past research[1] showing overruns occurring mainly due to design fault. Program problems such as cost and time overruns and product reliability through uncertain, inexperienced or negligent preliminary design decisions have resulted in program failure, company closure and industry instability.

The aerospace industry although growing is still suffering as a result of program cost overruns and delays. Companies are being forced to suspend programs such as Piper's Altaire program[2] and cancel initiatives such as GE's alternative F-35 engine program[3] due to uncertainty in developmental costs and schedules. This uncertainty has also lead to governments reconsidering their support of costly programs, and has prompted moves such as the defence bill being voted on by the US Senate that will see Lockheed "absorb the entire amount [of cost overrun] instead of splitting the increase with the US government."[4] Overruns are not new and even though methodologies are moving to address them, to date there has been no specific technique proposed that has the ability to predict potential overruns or in the very least, predict their impact.

Early engineering practices such as Systems Engineering (SE)[5], have ensured that the economic viability of programs is determined prior to development by calculating developmental, operational and disposal costs. This has been advanced with the introduction of Value Engineering (VE) and in particular Value-Driven Design (VDD)[6] which attempts to identify the program of greatest value to all stakeholders by performing unconstrained optimisations using value objective functions. However, as discussed in an assessment of the concepts in a study in 2011[1] existing methodologies and techniques are still incapable of reliably predicting the cost of aerospace programs due to the inadequate way in which they account for and manage uncertainty. Until uncertainty prediction and impact becomes a forefront and continuous consideration during product development, the accurate costing, value, robustness and ultimate success of a program cannot be determined.

The work and research that has been performed to date, which is presented in this paper, is aimed at advancing state of the art costing and valuation methodologies to allow for a program and design selection to be based not only on design merits but on how robust the design is against *foreseeable uncertainty*. Initially the phrase *foreseeable uncertainty* may seem counterintuitive owing to the fact that uncertainty in essence cannot be foreseen. In this context we define it as,

> *"obvious inherent uncertainty or variability of parameters within a design or pertaining to a circumstance about which assumptions or predictions can be made about their behaviour or contribution."*

It is the intention of this work to identify and automatically account for these foreseeable uncertainties when evaluating program or product cost and value. By way of achieving this aim a study of foreseeable uncertainties was performed[1], from which a new objective function for calculating realistic aircraft program value was determined. The function contained uncertainty coefficients relating to the foreseeable uncertainties bringing the current methodologies a step closer to automatic program uncertainty recognition and inclusion within calculations.

As summarised in the previous paragraph, the paper will begin by reviewing in more detail the research previously performed on the identification of cost and delay drivers and current costing methodologies. The developed Capability Function (CF), the end point of the previous work, will be reintroduced before discussing the most recent work. Results from an analysis of Surplus Value (SV) will be presented showing: the nature of the variables; stakeholder responsibility and control of the variables and the impact of the variables on SV and SV cost parameters. Given this analysis, the lowest level, independent and most influential variables will be identified. Uncertainty Factors (UFs) will be applied to these variables based on how the overrun drivers may affect them and as a result, a revised version of the CF will be presented.

II. Background and Work to Date

Program cost and time overruns are regrettably almost certain when new aircraft programs are developed. Cost and schedule are both determined within the early stages of the design development process, so it is reasonable to think that this stage should examine and plan for potential overruns. However, this does not seem to be the case with overruns tending to take developers by surprise. It is therefore important to gather a general understanding of where issues exist within the design process and identify why overruns are not anticipated.

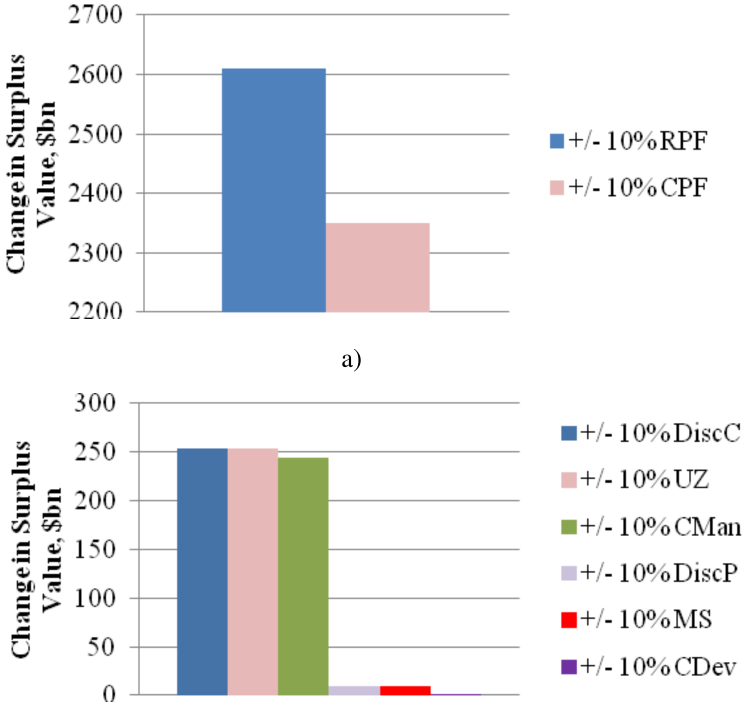
A study in March 2011[7] was initially performed on design strategies, assessing how they operated. Firstly Systems Engineering (SE) was investigated. It is no secret that historically, engineering and design often operated by an "over the wall" approach. This existed as a step by step process whereby the product was designed then ownership was handed to manufacturing, the next process. Unfortunately the concept behind SE functioned similarly with the lack of upfront "whole life" engineering and planning. Traditionally SE initially performs a requirements analysis followed by a functional analysis before generating a design. Processes such as manufacturing and maintenance are considered only after the function of the final design has satisfied customer requirements. It is understood that it is possible to offer feedback loops within the SE process to allow consideration of lifecycle stages but the ultimate decision will be based on whether or not the product satisfies the requirements. In addition to this, the SE process also relies heavily on the engineering experience of the designer and does not always ensure a repeatable process. Another issue with SE is the assumption that the design is correct, the consequent costing is accurate and the program will be completed correctly and in a timely manner. Of course ‘what if’ analysis can be performed but these are nothing more than blind sliding scales on parameters. Without knowing where the problems lie and their impact, it is impossible to determine the fragility of the program.

As a result of this, the theory behind VDD was examined in Fanthorpe et al.[7] and it was found that the methods involved encouraged “whole life” concurrent engineering, thus avoiding “over the wall” engineering. Using a value objective function that includes variables of interest to all stakeholders, the most valuable product in terms of economy, performance etc. is generated. A key to VDD is the maintaining of requirement flexibility, a theory not shared by SE advocators. Where SE seeks a product that first and foremost satisfies customer requirements, VDD seeks a high value product while allowing requirements to vary. However, as with SE, VDD still assumes complete program success. Again, only ‘what-if’ sensitivity studies aimed at approximating what could go wrong within the limitation of their formulated objective function can be performed when identifying issues.

Upon investigating SE and VDD methodologies work continued in beginning to develop a method through which overruns could be accounted for. Given the concurrent nature of VDD, it was seen that the theory offered a suitable platform from which addressing program overruns could be developed. In previous VDD studies[8] a formulation of the Surplus Value (SV) objective function was provided (Eq. 1). This formula used lifecycle attributes to calculate the total economic value of an aircraft program based loosely on Net Present Value (NPV).

$$SV = Disc_P \times MS \times [Disc_C \times U_Z \times (R_{PF} - C_{PF}) - C_{DC} - E_{TPF} - C_{Man}] - C_{Dev} \tag{1}$$

The SV was calculated initially for a baseline case of a fleet of 150 passenger jet transport aircraft modelled to be travelling from Belfast International Airport to Paris Charles de Gaulle and resulted in a SV of $44.1bn. From this case, work began assessing sensitivities within the SV function to identify the most volatile parameters[9]. It was identified that when varied +/-10%, the parameters within the current SV objective function impacted SV as shown in Fig. 1.



a)

b)

Figure 1. Change in surplus value as a result of varying a) R_{PF}, C_{PF} and b) $Disc_C$, U_Z, C_{Man}, $Disc_P$, MS, C_{Dev}

It can be seen that the parameters with the greatest impact are revenue per flight (R_{PF}) and cost per flight (C_{PF}). Revenue is a function of ticket price, which is controlled by the airline and passenger load factor that is an almost uncontrollable variable. Cost per flight is a function: of fuel cost; externality taxes; airport fees; crew costs and maintenance, all of which that are controlled by various stakeholders. Although not ranking high, the variation in the development cost (C_{Dev}) parameter is still within the range of millions of dollars, a continual loss no company could sustain. It is important to note therefore that any uncertainty in the high impact parameters will have a detrimental impact on the value of the program. The analysis performed above, which can be performed for both SE and VDD, allows the user to see how SV is impacted by the parameters but not what variation the parameters are subject to when a new program begins or as it continues throughout its lifecycle. It will be the identification and inclusion of the uncertainties on the parameters that will offer a novel approach to overrun prediction and estimation.

The next step in this work looked at identifying the main issues identified in past programs (4 commercial and 5 military applications) that contributed to time and cost overruns[1]. It was anticipated that the cost drivers could be coupled with parameters in the SV function to allow program SV to be adjusted depending on the design decisions made. Fanthorpe et al.[1] researched and collated the main program cost and delay drivers for the selected programs and found that a range of conditions contributed to cost overruns. The work categorised the conditions into six clusters whose contribution varied depending on the aerospace application (Fig. 2 and Fig. 3). These categories fell closely in line with the major contributing factors identified in a study by the Deloitte Aerospace and Defence group.[10]

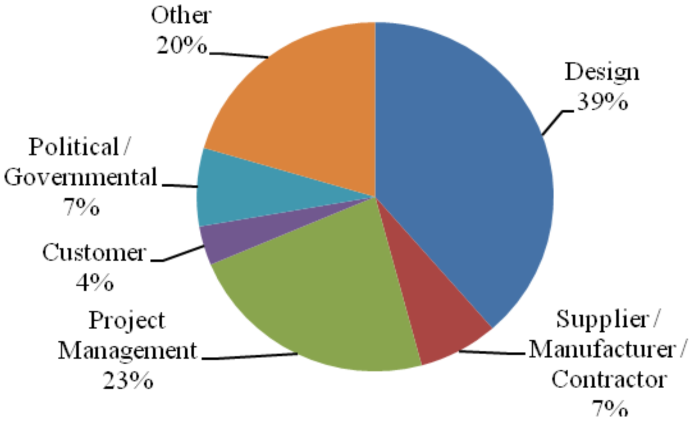


Figure 2. Military aircraft program issues for selected programs categorised into six main drivers and shown as percentages of total issues

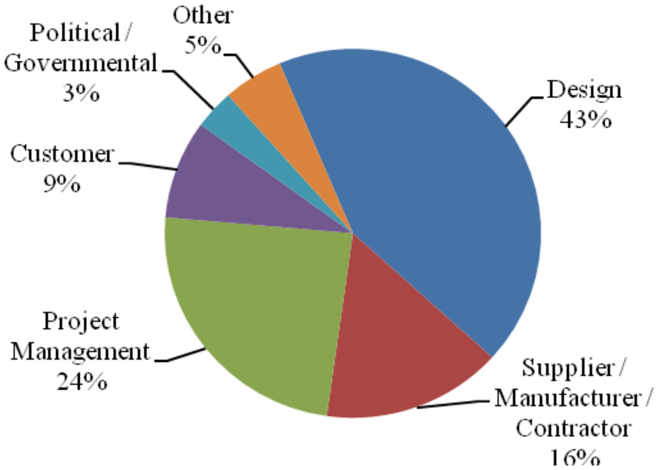


Figure 3. Commercial aircraft program issues for selected programs categorised into six main drivers and shown as percentages of total issues

The clusters seen in Fig. 2 and Fig. 3 are common to some extent among all new aircraft programs and it is from these six categories that the foreseeable uncertainty is determined. Based on design decisions, some aspect of the six cost driving clusters will impact aircraft programs so in effect we can predetermine this uncertainty, hence the use of foreseeable uncertainty.

Using the original SV function (Eq. 1) as a base, a new function was developed, known as the Capability Function (CF), shown in Eq. 2. The function has been adapted so that Uncertainty Factors (UFs) relating to the six cost driving clusters have been assigned to the appropriate SV parameter, allowing automatic consideration of design and decision uncertainty. As part of this work the original SV was rearranged so that E_{TPF} was included within the operating costs, a term relating to cost disposal (C_{Dis}) was added and C_{DC} was excluded since these eventualities are not a certainty and not within the control of the designer.

$$SV = F_{UC} \times \{ Disc_{P} \times MS \times [Disc_{C} \times (F_{D_r} \times U_{Z}) \times (R_{PF} - F_{D_r} \times C_{PF}) - (F_{SC} \times F_{Dr} \times F_{D_{in}} \times F_{PM} \times C_{Man}) - C_{Dis}] - (F_{D_r} \times F_{D_{in}} \times F_{PM} \times F_{D_{comp}} \times C_{Dev}) \} \quad (2)$$

Given the current state of the CF it can be seen how much uncertainty affects the model and what type of cost driver impacts each top level parameter. What cannot be determined is how heavily the uncertainty can impact the parameter and in what manner. The initial form of the CF shown in Eq. 2 is the current state of the art in this approach. The next section of this paper will detail recent advancements in the development of the UFs relationships with the SV parameters, before arriving at a final approximation of the CF. Determination of UF percentage impact on aircraft programs will not be discussed in this paper but will follow in later work.

III. Inherent and Realistic Surplus Value Relationships

In previous work[1] a general assessment of cost drivers and their behaviour was performed. Before determining the UFs a similar study must now be performed for the variables within the SV function in order to determine:

- Relationships of the variables – how they are connected and fed through one another
- Nature of the variables – dependant or independent, controllable or uncontrollable, frequency of occurrence within SV
- Ownership of the variables – who determines what variable within the function and how much control over their variables do they have
- Behaviour of the variables – positive or negative impact on SV and costs within SV
- Magnitude of impact of the variables – Influential or irrelevant to SV and costs within SV

By generating the information above, it will be possible then to isolate those variables that can be controlled by the designer or manufacturer, variables that are independent and variables that have the biggest influence on program SV. Through focusing effort on these variables and the uncertainty associated with them, an immediate advancement in uncertainty management will be achieved, moving towards more realistic costing and SV methods.

Initially a diagrammatic hierarchy of the formulated SV function was produced in MS Office Visio 2007®. Using this hierarchy it was noted that there are 9 levels within the SV function and a total of 169 variables. Coupling a Matlab® formulation of the SV equation and the hierarchy, the nature of the variables are summarised in Fig. 4.

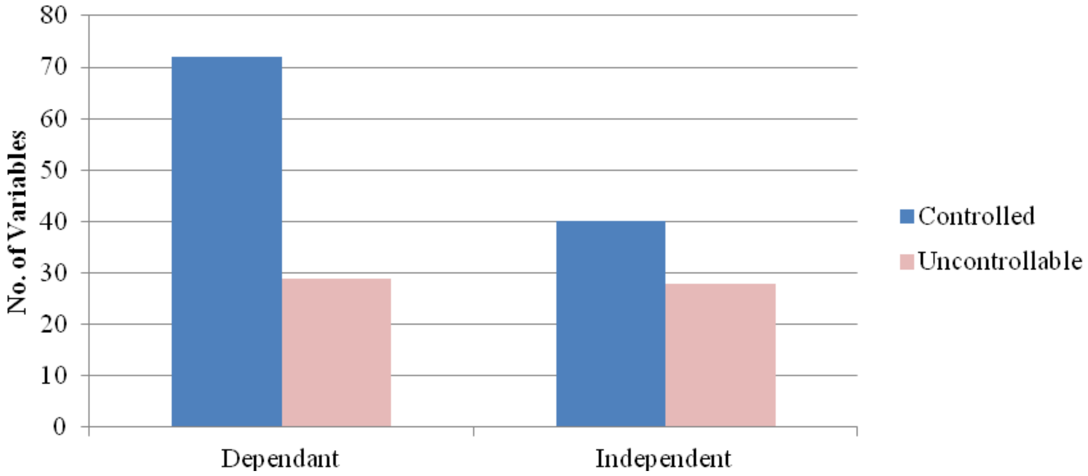


Figure 4. Surplus value variables grouped initially by dependency then grouped further by control

Figure 4 shows how the variables are categorised based on dependency and control. There are 101 dependant variables i.e. those generated though calculations based on the independent variables, and 68 independent variables which are user inputs. There are 112 controllable variables i.e. determined by customer, calculation or regulation etc, and 57 that are uncontrollable. Variables that are uncontrollable are noise factors such as salaries and finance factors, or those that tend to be consequential. Initially this program will look at the independent variables and will begin by applying UFs to the controlled variables. Given that there is a high quantity of uncontrollable variables effort will also be made to assess whether potential trends in these variables can be quantified. If some knowledge about their behaviour is known then there is a possibility that more accuracy can be built into any developed modelling techniques.

Now that the variables have been roughly defined, the next focus was to determine the group or stakeholders that determine each of the variables. Figure 5 shows a breakdown of the SV function and how each of the top level parameters can be broken down into stakeholders. In this instance stakeholders are defined as a group or department that is predominately associated with or responsible for the determination of the variables.

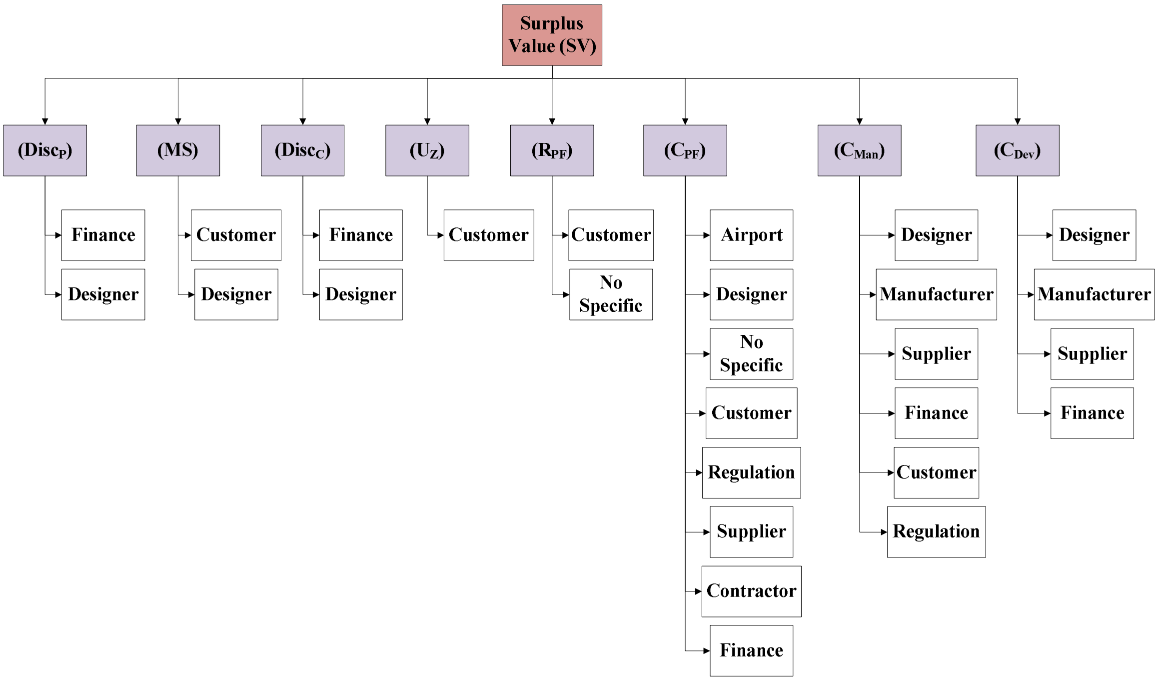


Figure 5. Surplus value hierarchy showing the associated stakeholder group for each of the parameters

Within the hierarchy there are nine groups. Up until this point the designer and manufacturer have been classed as individuals. Within industry the designer and manufacturers are combined within one enterprise e.g. Airbus and Boeing, so from this point forward the designer and manufacturer will be classified as one group, reducing the total number of stakeholder groups to eight. A description of each of the eight stakeholders is given below.

- ***Designer/Manu*** refers to any variable a designer or manufacturer determines or can have a direct impact on
- ***Regulation*** deals with variables determined by bodies such as governments, FAA or CAA
- ***Airport*** refers to variables determined by airport such as landing fees
- ***Supplier*** variables are those determined by part suppliers e.g. avionics, engine
- ***Contractors*** are variables relating to subcontractors for services such as maintenance (assuming the airline lease the maintenance).
- ***Customer*** variables are those determined by the purchasing airline
- ***Finance*** - banks, loans, financing, discount rates, cash flow
- ***No specific*** are variables without an immediately obvious or significant associated group with respect to the major stakeholder breakdown e.g. fuel density or salary premiums

Once the stakeholders and their influence on the SV function have been established, it is possible to determine how many variables they are responsible for and whether or not they have control over them. Having coupled the diagrammatic hierarchy of the SV function and Fig. 5, this information is shown in Fig. 6.

It is important to note that the information shown is only quantity of variables. It is possible that one stakeholder could be responsible for many variables but each with minimal impact. Quantity of variables does not necessarily equate to influence however, the information gained from this can still show useful interactions.

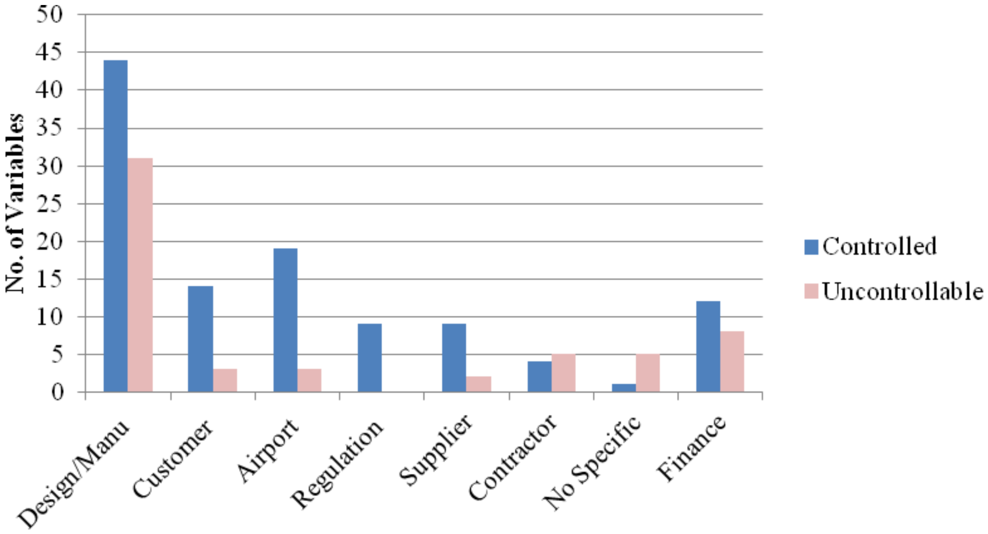


Figure 6. Surplus value variables grouped initially by associated or determining group and further by control

Using this information it is possible to establish groups with the greatest responsibility and if that responsibility is controlled. Both the customer and airport groups have high responsibility and control the majority of their associated variables. Regulation stakeholders control all their variables while the contractor group, for example, have more uncontrollable variables than controlled. It is clear from Fig. 6 that the designer and manufacturer (assumed to be one service like Airbus or Boeing) retain greatest responsibility relating to the SV formulation. However, it must be noted that there are many uncontrollable variables within this set. It is therefore as important to capture fluctuations in the uncontrollable variables as it is to capture it within the controlled. Failing to do so could cause a wash out in the benefits of performing overrun prediction.

The work continued by assessing specifically the variables controlled by the design and manufacturing group. Figure 7 categorises the “Design/Manu” variables initially by the design stage at which they are determined and then by whether or not the designer or manufacturer has control over them.

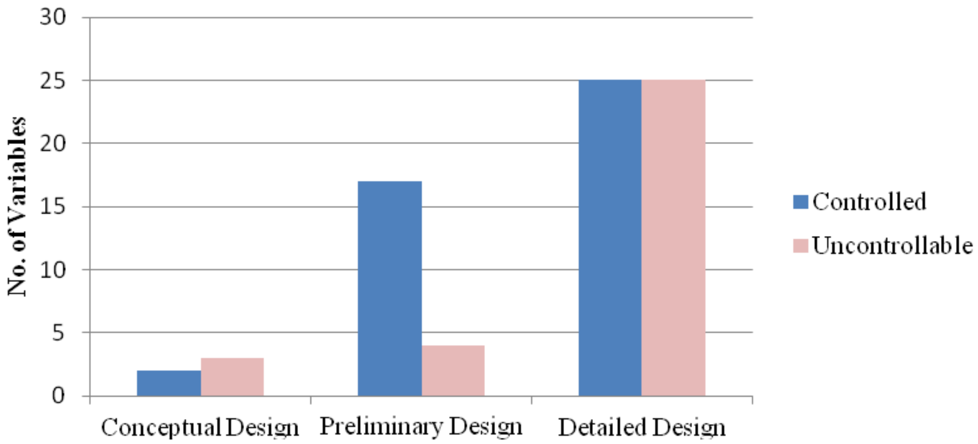


Figure 7. Design associated variables grouped initially by the design phase in which they are determined and further grouped by the control of the variable the design has at each phase

From the above graph it can be seen that irrespective of the continual request for concurrent engineering it is obvious that the vast number of design decisions are made in the later detailed design phase. Within the product lifecycle the majority of costs and commitments are locked down at the conceptual design stage. However, given the information in Fig. 7 it would seem that these costs are calculated and commitments made at a stage where very few variables have actually been decided on. With this in mind, it would be suggested that design decision making should be brought forward in the process, making as much information available at the earliest possible opportunity. Ideally it is envisaged that if design choices are made sooner and tested, then the chance of them causing issue at a later, critical lifecycle stage will be reduced. In some cases this is true however it is possible that making decisions sooner can lead to other less obvious issues. If a decision of high uncertainty is brought to an earlier design phase there is a chance that the effort in continual rework and testing will cancel out the benefit of moving it.

An alternative to this would be to calculate costs and make commitments later in the process; an unlikely case given the need for business proposals before programs commence.

Although the variable information has been generated using a simplified SV formulation it is possible to see the number of variables required. With the added complexity of aerospace systems, the required variables will increase dramatically, resulting in complexity becoming a potential driver of delays and cost overruns.

From Fig. 7 the ratio of controlled to uncontrollable variables is interesting. At the conceptual stage the uncontrollable variables are slightly higher than the controlled (3 and 2 variables respectively). In the preliminary design stage the controlled variables outnumber the uncontrollable (17 and 4 variables respectively) while at the detailed design phase the controlled and uncontrollable variables are equal (25 variables each). Again this trend encourages the analysis of the uncontrollable variables as much as the controlled if there is to be a significant improvement in SV and costing techniques when predicting overruns.

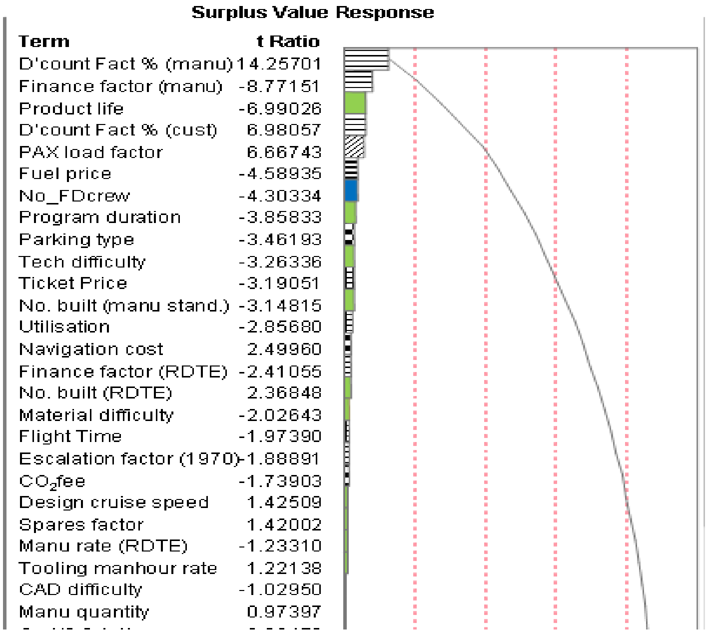
Upon assessing the SV sub-variables and the stakeholders responsible, the impact of the variables upon SV must be assessed. Until this point the focus has been on the quantity of variables and not their impact. In the following analysis the independent, variables both controlled and uncontrollable for all ownership groups were identified. Primarily this research is interested in the impact the variables have on cost and overall SV. It can be seen in Eq. 3 that SV is a function of three main costs; cost per flight (C_{PF}), cost of manufacture (C_{Man}) and cost of development (C_{Dev}).

$$SV = f\,(C_{PF,}\, C_{Man,}\, C_{Dev}) \tag{3}$$

Using the SV formulation, a fractional factorial DOE and screening effects test within JMP® was performed. From this data Pareto charts showing each of the variables impact on SV, were created (Fig. 8 and Fig. 9). The aim of this is to identify those variables with the greatest influence and those with little or no influence. Along with showing the response of each of the costs and SV to the variables, the bars have been coloured to identify the responsible stakeholder. Table 1 shows the stakeholder group colour coding.

Table 1. Colour coding for stakeholder identification in Pareto plots

Design/manu	🟩	Contractor	▥
Regulation	🟦	Customer	▦
Airport	▤	Finance	▤
Supplier	▧	No. specific	▨

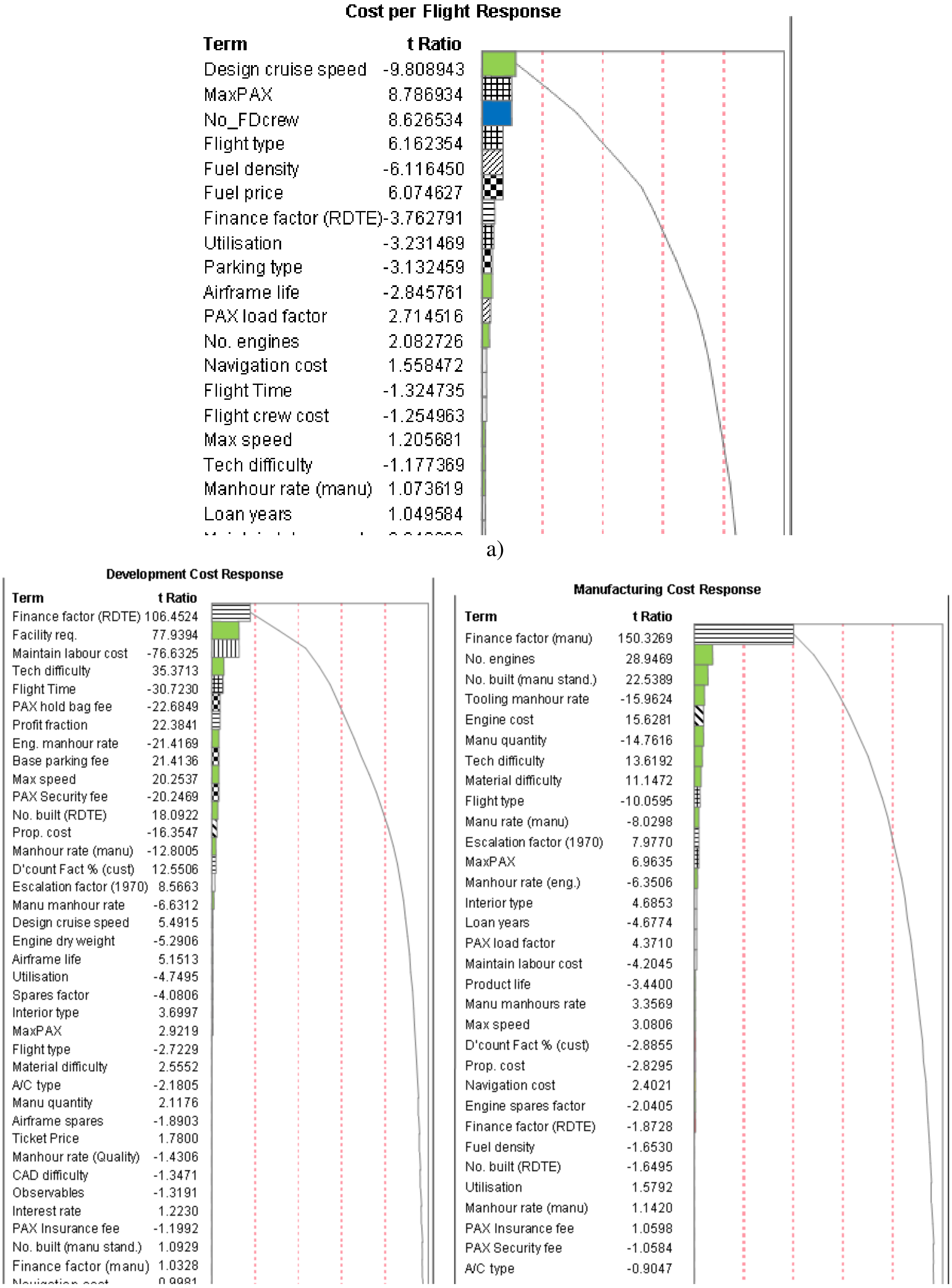


Surplus Value Response

Term	t Ratio
D'count Fact % (manu)	14.25701
Finance factor (manu)	-8.77151
Product life	-6.99026
D'count Fact % (cust)	6.98057
PAX load factor	6.66743
Fuel price	-4.58935
No_FDcrew	-4.30334
Program duration	-3.85833
Parking type	-3.46193
Tech difficulty	-3.26336
Ticket Price	-3.19051
No. built (manu stand.)	-3.14815
Utilisation	-2.85680
Navigation cost	2.49960
Finance factor (RDTE)	-2.41055
No. built (RDTE)	2.36848
Material difficulty	-2.02643
Flight Time	-1.97390
Escalation factor (1970)	-1.88891
CO_2fee	-1.73903
Design cruise speed	1.42509
Spares factor	1.42002
Manu rate (RDTE)	-1.23310
Tooling manhour rate	1.22138
CAD difficulty	-1.02950
Manu quantity	0.97397

Figure 8. Surplus value response to +/-10% variation in variables with a t-ratio greater than 1

In Fig. 8 it can be seen that SV is not impacted greatly by any particular variable; rather, multiple variables have a similar impact. What can be noted from the Pareto is that within the top five, finance variables occur three times. The discount factors for producer and customer featuring high is no surprise but it is not immediately intuitive that the manufacturing finance factor would have a high impact. Along with finance stakeholder variables, design and manufacturing stakeholder variables appear frequently within the Pareto with varying impact on SV.



a)

b)

c)

Figure 9. Response of a) cost per flight (C_{PF}), b) cost of development (C_{Dev}) and c) cost of manufacture (C_{Man}) as a result of +/- 10% variation in surplus value variables

As with the SV response to variable variation, the cost per flight response does not have a major sensitivity to any one variable but a similar sensitivity to multiple. Design cruise speed, a design and manufacturing stakeholder variable, has the highest impact which is understandable since this would determine fuel usage; an assumed key variable in flight cost. However, it is surprising to see that even though it has a relatively high impact, fuel price has one third less impact on cost per flight than cruise speed. Within the cost per flight response analysis, the variables associated with the customer features most frequently, with two having significant impact.

Looking at the cost of development response to variation it can be seen that again a finance variable has the greatest influence. Design and manufacturing variables are the most frequently occurring variable. The impact of the maintenance variable associated with contractors is surprising in this case since it is primarily incorporated with the cost per flight parameter within SV and not within development.

From the manufacturing cost response to variable variation it is obvious that finance has a major impact in this case which is expected. It is no surprise that the design and manufacture variables appear most frequently however, even when their effects are combined, the impact is still less than the impact of the finance variable.

Previously, when assessing the stakeholders with the greatest variable count it was seen that the most responsible stakeholders, in rank order were: design; airport; finance and customer. However, it can be seen from this SV impact analysis that this order does not necessarily hold true with finance, for example, having a higher impact in most cases than design. This is different to the previous study showing that the quantity of variables controlled by the stakeholder does not necessarily mean they have the greatest impact. It is important to identify this information so that high impact variables are not overlooked when identifying cost overrun and delay drivers.

IV. Capability Function

Now that the relationships and impact of the variables within the applied SV formulation have been investigated, this information can be used to justify Uncertainty Factor (UF) allocation within the Capability Function (CF).

The initial approximation of the CF (Eq. 2) highlighted, at the highest level, where potential uncertainty arose relating to the researched cost and schedule overrun drivers (Fig. 2 & Fig. 3). Now that the most influential, independent variables within the SV calculation have been identified, the CF can be adjusted to specifically account for the uncertainty within these. Since the influential, independent variables appear in the lowest levels of the hierarchy, if UFs are applied there, it is believed that the effect of the UFs will translate upward through the function. An example of how this occurs is shown in Fig. 10.

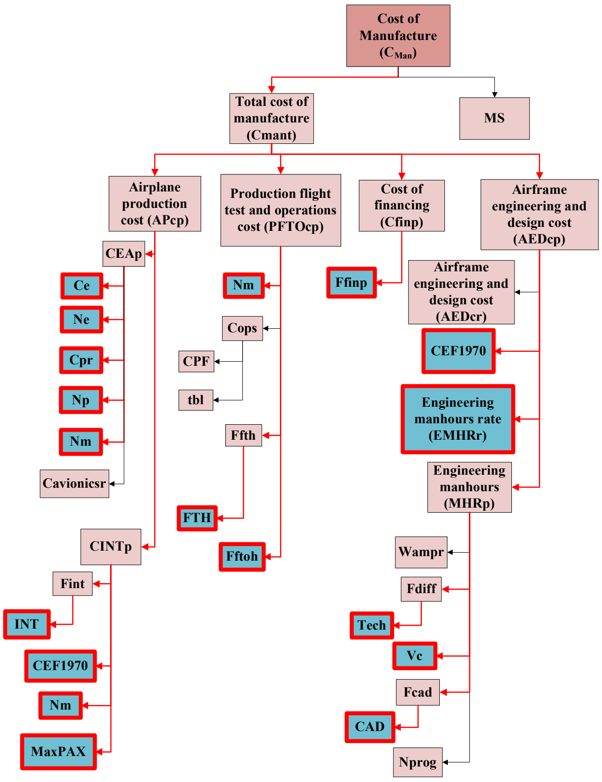


Figure 10. Section of SV breakdown showing an example of where uncertainty factors will be applied and how this will impact higher levels

The hierarchy above is a section of the manufacturing cost breakdown within the developed SV hierarchy. The lowest level variables highlighted above are a sample set of the influential, independent variables to which the UFs will be applied. The diagram does not explicitly show the UFs but represents their location and the flow of information up through the hierarchy.

Using the variable analysis above coupled with the SV hierarchy diagram, each of the 56 influential, independent variables are assigned UFs based on whether the variable could possibly be impacted by each of the researched overrun drivers. Assuming that the UFs are fed up through the hierarchy to the top level parameters, a second approximation of the CF has been produced below (Eq. 4).

$$SV = \alpha Disc_{P} \times \alpha MS \times [\beta Disc_{C} \times \gamma U_{Z} \times (\alpha R_{PF} - \alpha C_{PF}) - \alpha C_{Man} - C_{Dis}] - \alpha C_{Dev} \tag{4}$$

Where:

$$\alpha = f(F_{SC}, F_{Dr}, F_{Din}, F_{PM}, F_{UC}, F_{Dcomp}) \tag{5}$$

$$\beta = f(F_{Dr}, F_{Din}, F_{PM}, F_{UC}) \tag{6}$$

$$\gamma = f(F_{Dr}, F_{UC}) \tag{7}$$

It is clear from this improved adaptation of the CF that there is greater uncertainty within the original SV function and initial CF than first anticipated. The previous CF showed assumed uncertainty only associated with the top level parameters. However, on closer inspection of the variables, it is clear that there is more uncertainty within the sub-levels of the SV formulation. It is apparent therefore, that performing a top level sensitivity analysis is not sufficient in capturing all uncertainty; a possible reason behind current methodologies failing to accurately predict costs and issues. In Eq. 4 it can be seen that no UFs are assigned to the cost of disposal parameter (C_{Dis}). This parameter has not been evaluated as part of this work but once developed, the appropriate UFs will be assigned if necessary. Now that a greater appreciation of potential uncertainty has been developed, the research can proceed in quantifying the effects. This work provides the initial steps in predicting and *foreseeing* potential uncertainty and as a result, predicting and quantifying overruns.

Unlike the previous CF equation the parameters in Eq. 4 are described as being functions of the UFs. It must be noted that the UFs in each case could potentially differ depending on the variables with which they are associated. The value of and operators relating the UFs to the SV parameters cannot be determined until information on how the variables have behaved in past programs has been researched. This aspect will be developed in future work.

V. Conclusions

Given the previous research effort, this paper has provided the necessary knowledge required to make informed decisions on how best foreseeable uncertainty can be captured within VDD techniques.

Work completed to date has:

- Formulated the SV function and assessed its sensitivity to the top level parameters
- Identified the main cost and delay drivers from past aircraft programs
- Developed an approximation of the overrun predicting CF

This paper looks specifically at:

- Developing a hierarchical breakdown of the SV function
- Established where stakeholders fell within the SV function
- Identified the variables stakeholders are responsible for and whether they could control them
- Looked at where in the design process decisions about variables are made
- Developed Pareto plots showing the response of SV cost parameters and SV to variable variation
- Determined the most influential variables on cost parameters and SV
- Generated an improved version of the CF

The work performed to date on variable assessment will allow uncertainty to be captured within the most influential, lowest level design variables. By doing so, foreseeable uncertainty will effectively be built within a Value Driven Design framework allowing overruns and delays to be predicted.

VI. Future Work

Research within this area will continue by generating a database of extensive historical information regarding aircraft programs that have experienced overruns and delays. This information will be used to determine UF ranges and their operators within the CF.

To date overruns that have been included within the CF have only looked at directly mapping *cost* from design variables. Research will also be performed on how schedule shift impacts the developed CF and how this too can be built into the function to fully capture the effects of all overruns.

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