



Quantitative and Qualitative Cost Estimating for Engineering Design

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Abstract

This paper describes the development of a cost estimating methodology for predicting the cost of engineering design effort during the conceptual stages of product development. The research was carried out within a large European aerospace manufacturer whose traditional costing practices had become outdated. The main objective was to generate a suite of technical Cost Estimating Relationships (CERs) that integrate both quantitative and qualitative, non-recurring airframe engineering input, for the design process. Both the quantitative and qualitative design activities were separated during the CER development. At the end of the development process they were integrated to produce a final CER. The results demonstrate that these newly generated CERs can predict future design effort required, based on the typically limited product definition at the conceptual design stage.

1 Introduction

Aerospace industry is moving toward a system of concurrent or simultaneous engineering to improve competitiveness. Concurrent engineering reduces lead-time by

integrating the skills of functional disciplines into project teams, in order to design the product “right-first-time.” The company under investigation recognised that their traditional costing practices were outdated and not suited to this new type of environment. New Cost Estimating Relationships (CERs) were required to represent the changes within their working practices, particularly for the engineering design phase. Therefore, an initiative was required to formalise the process of developing a costing methodology for design engineering CERs, since there was a lack of the engineering CERs for airframes.

The research described in this paper is a continuation of existing work within the cost engineering area of the company under investigation and at Cranfield University. Roy *et al.* [1, 2] recently demonstrated the importance of integrating both quantitative and qualitative knowledge for CER development. The quantitative issues in design costing are related to quantitative design time (direct time) that can be precisely (within reason) measured, such as the development time for a 3D model on a CAD station. This is only a part of the total design time; for example, designers often spend a lot of time thinking about the design problem, and within a concurrent engineering environment consult with other experts in the team. The extent of this additional time very much depends on the complexity of the product, designers’ experience, and the novelty of the product. Estimating this additional design time is not trivial, it is based on knowledge, experience and is often judgmental, and this part is termed as the qualitative design time (or indirect design time). Roy *et al.* concluded that the identification of and the integration of the two types of design times provides a much more accurate estimate of the design effort required to produce 3D CAD models.

The main purpose of this paper is to present the CER development methodology and demonstrate how the final CERs were used. This paper emphasises the importance of data collection, offers guidelines for CER development, and highlights the risks involved. The main challenges of the research are:

- How to capture indirect activities (and times associated with them) accurately, how to evaluate and use them for cost estimating;
- Establishing statistical relationships between the actual design time of a part to the available conceptual information for a new development, and;
- Developing questionnaires to capture the indirect activities as objectively as possible.

2 Related Research

Cost estimating and cost engineering are separate disciplines yet inextricably linked. Cost estimating refers to a commercial business process that provides the customer with an estimate of a product or service. Whereas, Cost engineering is more involved and concerned with design trade studies rather than that of providing estimates for commercial proposals. In both cost estimating and cost engineering, the USA leads the way in practice and development [3, 4]. In Europe the European Space Agency (ESA) actively promotes the sharing of cost estimating and engineering best practices [5]. There are numerous cost estimating/engineering projects being funded within the UK [6, 7, 8, 9, 10, 11]. Nonetheless, throughout available literature only a small number of papers discuss cost estimating issues surrounding the design process. Moreover, hardly

any of them explicitly consider the qualitative (thinking) design time as a part of the total design effort.

Both cost estimating and cost engineering involve a number of quantitative and qualitative criteria and issues, which are well recognised [1, 2, 12, 13, 14]. Several authors discuss methods for developing CERs for the development process, but do not attempt to make a distinction between the thinking and non-thinking time during this process [4, 15]. A typical example of this can be found in Meisl's cost model for predicting the development and production costs of solar power space systems [15]. The CERs used to estimate the development costs are based on the development costs of recent projects. Factors are applied to these CERs so that the model can be adjusted to predict the cost of a new product. However, the experience of the design team, complexity of the product, and the relationships between thinking time and non-thinking time are not explicitly considered. Thus, although authors recognise design experience and product complexity as having a significant impact on the amount of development time needed [16], the process of measuring the design team experience and their impact on the total design time has not been considered.

The two main cost estimating techniques utilised within this research are Parametric cost estimating (PCE) and Feature based costing (FBC). PCE is a method used to estimate the cost of future systems. It is typically used during the early stages of development, when there is little product information available. The main principle of PCE is to develop a statistical relationship between the attributes and cost of previous products in order to predict the cost of a new product. Industry and Government accept

the techniques and many authors commend its usefulness, such as: DOD [4], Busby *et al.* [12], Zhang *et al.* [17], and Pugh [18]. FBC is a relatively new form of parametric estimating. Choices regarding the inclusion or omission of a feature impact the downstream costs of a part, and eventually the life cycle costs of the product [19]. Several researchers investigate the integration of design, process planning and manufacturing for cost engineering purposes using a feature based modelling approach [20, 21, 22, 23]. Therefore, product features were used within this research, to assess their applicability within the CER development process.

The remainder of this paper presents the CER development methodology and the results, section three moves on to describe the design process for which the CERs were developed.

3 The Design Process: Context

Figure 1 below depicts the order of air system development during the technical design activities. Integrated product development (IPD) is carried out from the concept of a product to the first article build. The focus of study for the creation of CERs is also illustrated.

The integrated product team (IPT) consists of multifunctional members who produce the initial concept and project plan for the product. The initial scheming phase then begins and moves through various phases of definition, to the 3D model, and finally to the 2D model phases. The maturity freeze gates ensure all activities are complete to a

sufficient level of detail before moving through to the next project phase. Understanding and mapping this process, in consultation with the engineers, facilitated the identification of cost drivers for the CER development.

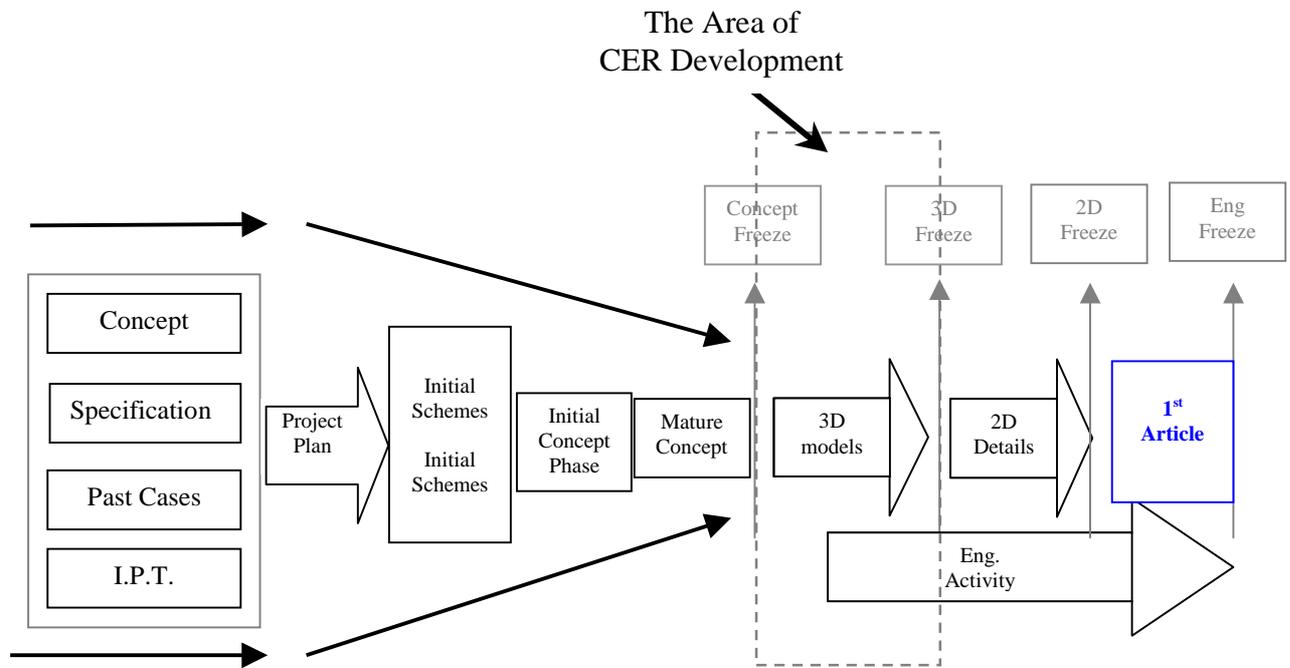


Figure 1. The IPD process followed by the I.P.T. through to 1st Article [11]

3.1 Design Cost Drivers

A cost driver is any factor that significantly affects cost. That is, a change in the cost driver will cause a change in the total cost of the product. Some cost drivers are financial measures found in accounting systems (such as direct manufacturing labour hours in financial terms) while others are non-financial variables (such as the number of parts per product).

3.1.1 Quantitative Cost Drivers

Quantitative cost drivers can be defined as a cost driver that can be given a precise value [24]. Examples of quantitative cost drivers used within an estimating process are: mass,

area, volume and quantity. For example mass, (a commonly used cost driver within the aerospace industry), is accepted as a known (quantitative) value during the conceptual stage of design from which to base a cost estimate. Within this research, quantitative cost drivers for the design activities relate to the actual time spent working at a CAD workstation. Consequently, the quantitative variables used to create the final CER were related to the number of draw elements such as: lines, arcs, and circles etc. that are recorded as the designer uses the CAD tool.

3.1.2 Qualitative Cost Drivers

Qualitative cost drivers can be defined as a cost driver for which it is difficult to assign a precise value [25]. A value can only be given through heuristic methods. Examples of qualitative cost drivers are: quality, complexity, material, and manufacturing processes. For example, estimators use judgement (subjective) and experience to decide how complex one product is in relation to another. Within this research, qualitative cost drivers relate to thinking time required for a given development. Consequently, the qualitative variables used to derive the CERs were related to the IPT experience and the perceived complexity of the 3D-model development.

After the quantitative and qualitative cost drivers were identified within the design process, the data required for analysis needed to be collected; this process is described in section four.

4 The CER development Methodology

4.1 Stages of CER Development

Figure 2 below illustrates how both the quantitative and qualitative CER were created independently before being integrated. The methodology started with the collection of available data at the conceptual phase (stage one of Figure 2) and available data at the 3D-freeze (stage two). To produce a predictive model, the conceptual information needed to be statistically linked to the time spent on a part; this process is described more fully in Section 4.3. At stage four, allocations for time related to discussions with mass and structural engineers were added to the qualitative CER. The allocations were estimates completed by the IPT leader and designer. At the end of the process the qualitative and quantitative CER were combined to produce a final cost estimate, as illustrated in stage five of Figure 2.

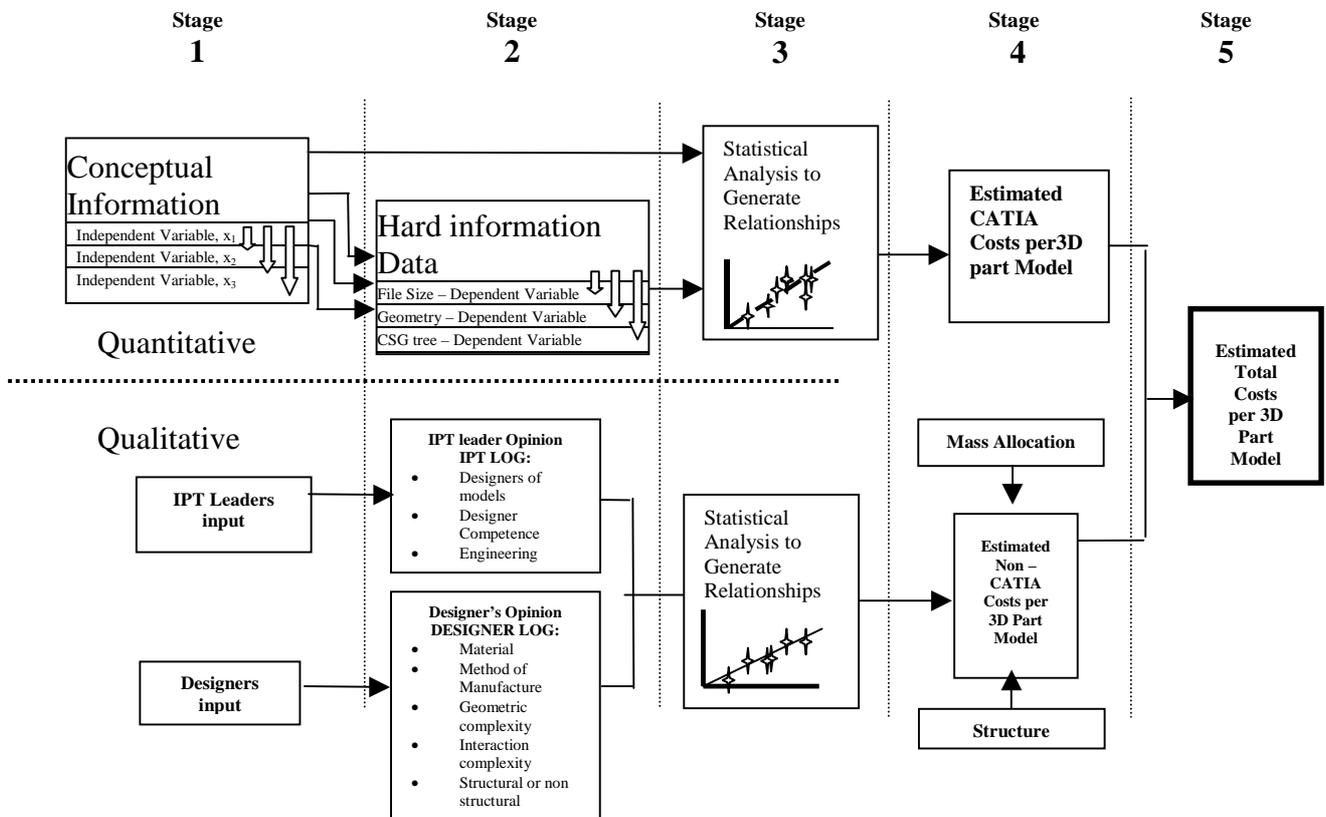


Figure 2. A Schematic diagram of the methodology

4.2 Data Collection

4.2.1 Quantitative Data

Two types of quantitative data were identified for the CER development: firstly data extracted from the CATIA system, e.g. draw elements and number of faces, and secondly, data extracted from the actual solid model within CATIA i.e. features (flanges, holes, and pockets). The features had to be extracted manually because they were not automatically defined. Collecting these two types of data meant that a comparison could be made between the draw element data collection method and the feature data collection method.

The data was collected from two phases of the product's lifecycle, the conceptual phase and the 3D-freeze phase. The conceptual information utilised was Mass. This had to be taken from the finalised 3D model but should, in future, be taken from the target mass which is available during the conceptual stage. Table 1 illustrates the types of quantitative data captured for the CER development.

EXTRACTION PHASE	TYPE OF DATA	SOURCE
Conceptual	Mass	3D Solid Model
3D Freeze	Number of Faces Number of Draw Elements	CATIA
3D Freeze	Number of Cut-outs Number of Flanges Number of Holes Number of Joggles Number of Lugs Number of Pockets Number of Stiffeners Volume	3D Solid Model

Table 1. Types of Quantitative Data

4.2.2 Qualitative Data

The qualitative data was collected using questionnaires, which were completed by both the designer and their IPT leader. The captured qualitative data provided an indication of the engineering experience and the complexity of the part, and thus, an idea of the thinking time required for modelling each part could be derived. Since there were no logbooks the designers had to estimate both the qualitative and quantitative hours spent modelling each part. For example, the ratio for one part could be 40/60 (%) at the 3D-freeze stage, which is illustrated in Figure 3. This ratio was adjusted according to the perceived complexity of the part being modelled.

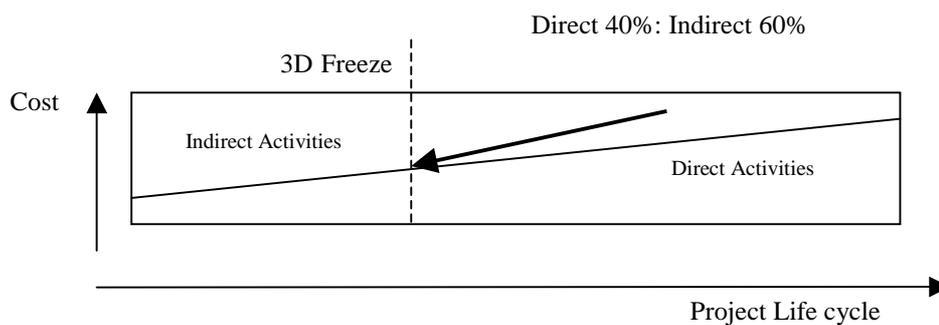


Figure 3: An estimated ratio between direct and indirect activities at the 3D freeze stage

4.2.2.1 Questionnaires

The following questionnaires are used to capture the qualitative inputs for the design.

IPT Leader's Questionnaire:

Name of IPT Leader: The name of whoever is filling in the costing log for the scheme.

Name of Project: The name of the current project.

Name of Scheme: The name of the scheme being rated e.g. Ancillary Equipment.

Scheme File Name: The file name for the scheme CATIA model at concept freeze.

Allocations: The amount of work completed by the non-design engineers during the design process of the IPT. Measured as a percentage of the total amount of work carried out by the design engineer on the same model. For example, the designer does 100% of design work on a model and a mass engineer may do a further 10% of the work completed by the designer.

Allocation for Mass: The design input, as a percentage, by the mass department.

Allocation for Structures: The design input to the model by the structural engineers. This is split into two types reflecting the different amount of work required. Structural parts which may require more work and finite element modelling and non-structural parts that may require less work.

Allocation for Assembly/Manufacture: The design input of assembly and manufacturing engineers to the design process.

Brief Description: A brief description of the scheme that will allow easier identification of the scheme and its function. Additional notes may also be entered in this space.

Designer's Questionnaire:

Designer ID: The code used to identify the designer who works within the department.

Designer CATIA experience: Years the designer has worked with the CATIA CAD system (including any experience acquired from previous employment).

Design Area Competence: The experience that the designer has in designing this type of manufacturing process. Measured as the number of parts, that has been designed within the specific manufacturing process.

Geometric Complexity: A measure of the complexity of the part shape with respect to the modelling and design difficulty. The parts were categorised from 1 - 4.

1. Simple prismatic geometry, e.g. cube, cone, etc.
2. Compound planar geometry, e.g. interacting planes
3. System related geometry
4. Surface related geometry

Surface Related Part: A question as to whether the part is surface related or not.

Interface Complexity: A measure of the complexity of the part or model, considering the number of sub parts and interfaces with other parts in the model. The parts were categorised from 1 - 4.

1. Secondary structure interface, e.g. supporting bracket
2. Primary structure interface, e.g. longeron interfaces
3. System interface
4. Major transport joints, e.g. front fuselage and rear fuselage joint.

Structural: Whether the part is a structural or a non-structural part.

Total Time Designing the Part: The time spent on designing the part from conceptual phase to 3D freeze, measured in hours.

Qualitative Time (Q^L): Qualitative time is the time spent on thinking, e.g. task solutions, mass/structure/manufacturing consultation, etc, for the specific part: The qualitative time spent on each part model is measured as % of the total time.

Quantitative Time (Q^N): Quantitative time is the time spent on modelling, e.g. modelling in CATIA. The quantitative time spent on each part model is measured as % of the total time.

A sample of how the quantitative and qualitative data was collected and stored is presented in Table 2 below. The next stage of the CER development was to statistically analyse it in order to identify any relationships between the data collected and the 3D-model development times.

File Name	CATIA Experience	Area Competence	Geometric Complex	Surface Related	Interface Complex	Structural	Qualitative Time	Mass(gram)	Area(mm2)	Vertices	Edges	Faces	Primitives	Draw Elements	Volume(mm3)	Wetted Area(mm2)	Holes	Pockets	Cutouts	Stiffners	Flanges	Joggles	Lugs	QUANT_TIME
x-01	3	5	3	0	3	1	60	251	28097	193	297	106	24	1	90000	106000	22	2	1	0	6	0	2	40
x-02	3	5	3	0	3	1	50	384	36231	269	416	154	23	1	137000	127000	50	4	4	0	5	0	0	70
x-03	3	5	3	0	3	1	70	461	49348	521	795	278	58	1	165000	160000	100	3	3	0	5	0	5	60
x-04	4	5	4	0	3	1	60	496	60682	451	707	261	75	1	178000	192000	50	5	3	4	4	0	0	40
x-05	4	5	3	0	3	1	60	481	38522	465	721	261	81	1	171000	143000	50	4	3	4	4	0	0	40
x-06	3	5	4	1	3	1	263	1963	258154	1084	1698	617	107	1	704000	702000	150	14	2	8	2	0	0	87.5
x-07	3	5	4	1	3	1	263	2078	252486	1274	1982	712	130	1	745000	742700	150	10	1	7	4	0	0	87.5
x-08	2	2	3	1	3	1	130	757	77384	552	796	276	130	1	272000	236000	30	6	3	4	2	0	0	70
x-09	3	5	1	0	2	1	50	460	34084	220	347	131	42	1	165000	111000	50	7	2	4	0	0	2	50
x-10	3	5	4	0	2	1	50	460	34084	504	793	291	45	2	165000	111000	50	7	2	4	0	0	2	50
x-11	4	5	4	1	4	1	150	1024	75794	220	347	131	42	1	367324	239572	30	6	1	5	3	0	0	100
x-12	4	5	4	1	4	1	150	1024	75794	220	347	131	42	1	367324	239572	30	6	1	5	3	0	0	100
x-13	2	2	3	1	3	1	130	745	76582	556	845	291	137	1	267000	233000	40	5	4	4	2	0	0	70
x-14	4	5	2	0	1	1	160	1942	201539	1789	2814	1023	172	1	696069	555759	120	20	8	20	8	0	0	240
x-15	4	5	2	0	1	1	100	723	83034	1037	1637	599	86	1	259214	255040	100	14	5	10	5	0	2	100

Table 2: A sample of the captured Quantitative and Qualitative data

4.3 Statistical Analysis

Linear regression analysis [26] was used to test for a relationship between the development time and the captured data. Linear regression measures the dependency of chosen variables in relation to other independent variables. Within this research the final quantitative and qualitative development time is dependent (the value that needs to be predicted), upon the independent variables (the values for which knowledge is available) of mass, surface related properties, and allocations. Therefore, a change in the values of the independent variables will cause a change in the final 3D-model development time.

Regression analysis is a widely used method for CER development amongst the cost estimating community [4, 18]. To establish which independent variables to use within the final CER, Factor analysis was applied. Factor analysis provides an indication of which variables are most relevant for the CER development [26]. Only the significant variables discovered from the Factor analysis are used within the final regression analysis.

Well-developed CERs are traceable; that is, they have an audit trail. This means that the general information available at the conceptual phase of a project needs to be tied to explainable cost drivers that appear as the part is modelled. This helps the company to receive buy in from both designers and customers when the CERs are used. Below follows an illustration of this process. The bold sections of each diagram depict the focus of statistical analysis during each stage of the process outlined above in Figure 2.

- 1) Firstly a relationship between time and the 3D-freeze data was developed with time as the dependent variable and 3D freeze data as the independent variables (Figure 4).

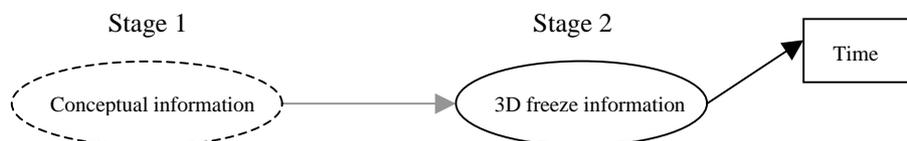


Figure 4. Relationship between time and 3D freeze data

2) Secondly, a relationship between 3D freeze data and conceptual information was developed, using 3D freeze data as the dependent variable and conceptual information as the independent variables (Figure 5).

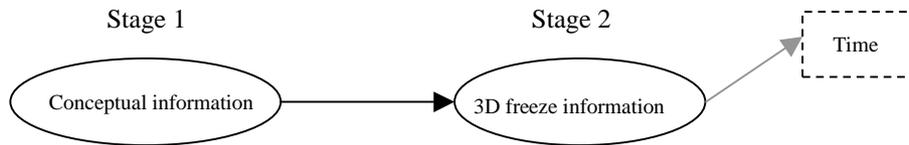


Figure 5. Relationship between 3D freeze data and conceptual information

3) Thirdly, the two relationships developed in 1) and 2) were combined into one relationship, with time as the dependent variable and conceptual information as the independent variable (Figure 6).

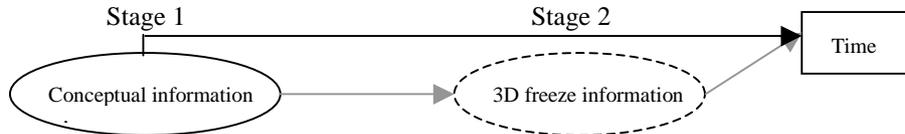


Figure 6. Combined relationships

The qualitative data was collected at the 3D-freeze stage from both the designer and IPT leader through the questionnaires. The type of questions included topics such as geometric complexity, designer’s experience, and likelihood of engineering change. The qualitative data captured at 3D freeze is also known during the conceptual stage of project development; therefore, a statistical relationship between the conceptual information, and time spent on the part was possible (Figure 7).

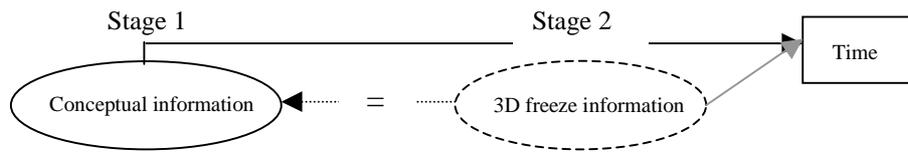


Figure 7. Qualitative data collection at the 3D-freeze stage

After the Equation was formed, a risk analysis and assessment was conducted on the final CER to provide a degree of confidence. However, the full details of this analysis are beyond the scope of this paper, but can be found through the following reference [27]. To demonstrate the CER development process more clearly the following case study is presented.

5 Case Study

5.1 Context and Model Identification

To test and validate the developed methodology, a case study was conducted within a specific area of a current project within the company. A small number of components were chosen in order that a thorough analysis could be completed within the time frame of the research. A series of workshops with IPT leaders and designers provided necessary understanding of the design process. Having developed an understanding of the design process, the data collection was undertaken. Fifteen models were identified (See Table 2) as suitable for validating the methodology. These models were all machined parts and fabricated from aluminium alloy.

5.2 Results

5.2.1 Quantitative CERs

The 3D-freeze information was gathered from the CATIA hard data, which was extracted from the CAD system, and low-level features were manually counted from 3D solid models.

- CATIA hard data based approach:

CATIA hard data was used at stage two (see Figure 2):

Stage two to four: correlating CATIA hard data at 3D freeze to quantitative time:

$$Quantitative\ time\ (Q^T) = C_0 + C_1 \times (No\ of\ Faces) \quad \dots\ Equ.\ 1.0$$

The statistical analysis provided a correlation coefficient of $R^2 = 0.57$.

Stage one to two: correlating conceptual quantitative information to CATIA hard data at the 3D freeze:

$$No\ of\ faces = C_2 + C_3 \times (Mass) \quad \dots\ Equ.\ 2.0$$

The statistical analysis provided a correlation coefficient of $R^2 = 0.63$.

Added together (Equ. 1.0 and Equ. 2.0) the relationship is as follows:

$$Q^T = C_4 + C_5 \times (Mass) \quad \dots\ Equ.\ 3.0$$

Where C_1, \dots, C_5 are constants.

- Low level feature based approach:

Low-level features were used at stage two (see Figure 2):

Stage two to four: correlating features at 3D freeze to quantitative time:

$$Q^T = C_6 + C_7 \times (No.\ of\ Stiffeners) + C_8 \times (No.\ of\ Flanges) \quad \dots\ Equ.\ 4.0$$

The statistical analysis provided a correlation coefficient of $R^2 = 0.79$

Stage one to two: correlating conceptual information to features at the 3D freeze:

$$\text{No. of Stiffeners} = C_9 + C_{10} \times (\text{Mass}) \quad \dots \text{Equ. 5.0}$$

The statistical analysis provided a correlation coefficient of $R^2 = 0.51$.

It was not possible to establish any meaningful relationship between the number of flanges and mass, thus flanges were not included in the final Equation.

Added together (Equ. 4.0 and Equ. 5.0) the relationship is as follows:

$$Q^T = C_{11} + C_{12} \times (\text{Mass}) \quad \dots \text{Equ. 6.0}$$

Where, C_6, \dots, C_{12} are all constants.

5.2.2 Qualitative CERs

The qualitative relationships were obtained by statistically analysing the information (potential cost drivers) captured from the questionnaires described in Section 4.2.2. The results are presented below:

- Direct relationship between conceptual qualitative information and qualitative time at 3D freeze phase:

Stage one to time: Qualitative relationship:

$$\text{Qualitative time } (Q^L) = C_{13} + C_{14} \times (\text{Surface related}) \dots \text{Equ. 7.0}$$

The statistical analysis provided a correlation coefficient of $R^2 = 0.58$

The above Equation did not seem totally logical because it did not contain one of the most important qualitative cost drivers, the designer's CATIA experience. With further investigation, it was observed that the data was not logical enough, especially in the

case of CATIA experience. This is a potential risk in using qualitative information. After consulting designers, it was decided that an additional percentage should be added to the total design time, based on the designer’s CATIA experience. If a less experienced designer is used when designing the part, 50% (for a high complex part) and 30 % (for a low complex part) should be added to the total qualitative time, this is termed ‘experience allocation’.

5.2.2.1 Allocations

The allocations of mass, structural, non-structural and assembly/manufacture were captured in the questionnaires filled in by the IPT leader (see 4.2.2.1 above). The allocations had to be added to the total qualitative time and are presented in Table 3 below as an additional percentage. This is termed as ‘multidisciplinary allocations’. There were no non-structural parts in the data set so it was therefore excluded.

<i>Discipline</i>	Allocations (% of Q^T & Q^L time)
Mass	5 %
Structural	35 %
Non-structural	0 %
Assembly/ Manufacture	15 %
Total	55 %

Table 3: Allocations for other disciplines

Therefore: *Total Qualitative Time* = $C_{15} + C_{16} \times (\text{Surface Related}) + \text{Experience allocations} + \text{Multidisciplinary allocations}$... Equ. 8.0

5.2.3 Final CERs

With respect to the previously described Equations above, the final CERs are described:

- Based on CATIA data (Equ. 3.0 and Equ. 7.0):

$$\text{Total design time} = C_{17} + C_{18} \times (\text{Mass}) + C_{19} \times (\text{Surface related}) + \text{Allocations based on the qualitative time (Equ. 8.0)} \quad \dots \text{Equ. 9.0}$$

- Based on Low level features (Equ. 6.0 and Equ. 7.0):

$$\text{Total design time} = C_{20} + C_{21} (\text{Mass}) + C_{20} (\text{Surface related}) + \text{Allocations based on the qualitative time (Equ. 8.0)} \quad \dots \text{Equ. 10.0}$$

Where, C_{15}, \dots, C_{20} are constants.

5.3 Validation of the developed CERs

The CERs were validated using two stages. The first stage was to verify the statistical analysis process, and the second was to validate the process with the company experts. Due to non-availability of data the CERs could not be applied to a new set of designs for further validation. The final CERs proved logical, because the derivation of each variable could be easily explained. However, the correlation coefficient for most of the CERs was low, this was mainly due to the small number of poor quality data, but could also be a result of the variable nature of the design process. Currently, there is no other method that the company can use to estimate the future cost of design time for airframes, thus the results presented in this paper are very useful for the company. It was also observed that both the Equations (Equ. 9.0 and 10.0), one based on CATIA data and the other based on manually counted low level features were similar, thus validating the credibility of the feature based approach.

The development and validation of the above methodology exposed the authors to several challenges. The key lessons learned from the experience are presented below; this should facilitate future CER development of the type described within this paper

6 Guidelines for CER development: Lessons Learnt

The authors advise observance to following guiding rules of thumb:

1. Understand the design process first;
2. Do not mix too dissimilar products for the CER development;
3. Collect as much data as possible for as many designs as possible;
4. Verify the quantitative data for physical significance;
5. Cross check the qualitative data, take more opinions;
6. Educate designers about quantitative and qualitative cost drivers;
7. In the real life design environment, the amount of data is a problem, do not depend entirely on statistical analysis to develop the relationships, use common sense and experience too;
8. Always identify and make explicit the qualitative or judgmental issues within the costing process, this will help to reduce the risk;
9. Do not use too many variables within the CERs, this will increase the maintenance cost and make long term use impractical;
10. Do not mix the quantitative and qualitative cost drivers during the analysis, treat them separately, and;
11. Always validate the CERs for physical significance with the designers.

7 Discussions

When new CERs are developed, consideration must be given to the fact that all projects are different i.e. the development stage of the project, the CAD tool used, and the designer's experience need to be captured in order to create a valid CER. The final CER

was developed using information obtained from a group of parts (i.e. part family), which were designed for a specific project. Therefore, these CERs should be used only on similar part types.

There were no logbooks kept by the designers on the examined project, consequently there were no actual times booked for each part. Therefore, it was necessary to capture the development time by asking the designers involved with modelling the parts. The designers estimated the total time and the ratio between time spent on quantitative and qualitative activities. Because of this approach, there is still considerable uncertainty within the estimate, which can affect the final result. In addition, there are further subjective questions related to the allocations of mass, structure, manufacturing, and assembly. These were estimated as a percentage of the qualitative time and therefore involve more uncertainty and added risk. In order to increase the validity of design thinking time, designers need to log the indirect time related to the part being developed and modelled. This is not a trivial matter since designers are not accustomed to measuring their working time for analysis. This will be a difficult task for all companies that undertake such a project.

The final qualitative CER included only one qualitative variable, surface related. The impact this variable has on the final CER is logical. The time to design a part increases when a part is surface related. Variables that are excluded during the analysis are, among others, the designer's experience and competence. This is not logical, since logic dictates that a more experienced and competent designer should have an effect on the outcome, i.e. lower design time. This issue is addressed through discussion with the

designers and by adding ‘experience allocations’ to the qualitative time. This is purely subjective and can add to the risk. Nevertheless, it is possible to quantify the risks involved within the CERs and therefore a risk analysis should be carried out. A risk analysis will help to manage the risks before they actually occur [27].

One of the questions examined was whether CATIA data, or low-level features should be used in stage two of the development of a quantitative CER (see figure 2). The total quantitative CER shows slightly better results when low-level features are used. However, the data set was too small to rely on the result, this needs to be further examined before the CATIA data can be removed from consideration.

8 Conclusions

The research described within this paper recognised the fact that estimating design effort is not a widely researched topic area, and furthermore, that CER development needs to consider both the direct and indirect design times to improve estimating accuracy. Therefore, this paper presented a methodology for developing CERs that explicitly consider and capture both quantitative (direct CAD working time) and qualitative (design thinking time) design times during the CER development process. These CERs can be used to more accurately predict the development time of 3D-models on a CAD workstation. The methodology reduces the subjectivity of CER development through the separation of the qualitative and quantitative issues before adding them together to produce a final CER.

The qualitative data was captured through designed questionnaires. This makes the CER development process more repeatable and therefore, scientific. However, not all-subjective issues could be removed through the questionnaires. Furthermore, statistical analysis, on its own was not effective to create the final CERs. Common sense, experience and logic were required to improve the relationships. Accounting for qualitative issues during the CER development process is a complex matter. Nonetheless, the methodology described in this paper both emphasises and challenges these issues to improve the cost estimating accuracy of total design effort.

9 References

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