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Function-Based Cost Estimating

Rajkumar Roy¹, Petros Souchoroukov¹ and Terry Griggs²

¹ Decision Engineering Centre, Cranfield University, Cranfield, Bedford, MK43 0AL, UK.

Email: r.roy@cranfield.ac.uk and psouchoroukov@yahoo.co.uk

² Ford Motor Company, Room 762, Trafford House, 8 Station Way, Basildon, Essex, SS16 5XX, UK.

Abstract

Communication between cost estimators with commercial (CE-C) and engineering (CE-E) backgrounds is essential for good internal practice. This paper presents a Function-Based Cost Estimating (FUCE) framework to link the commercial and engineering communities through a structured approach at the conceptual design stage. The objective of FUCE is to translate the unquantified terminology and the requests associated with the product specifications used by CE-C into a medium that CE-E can process using their resources, and creates estimates that are based on a standardised approach. The FUCE approach starts with functional decomposition, and then identifies product parameters that are related to a top level function and finally associate product costs to the function using past knowledge and data. FUCE is developed using a detailed case study on an automotive exhaust system. The methodology is then validated on two case studies from automotive and aerospace industries.

Keywords

Cost Estimating, Cost Improvement, Costing, Function-based Cost Estimating, Design, Conceptual Design

1.0 Introduction

Manufacturing industries operate in a very competitive market. Competitiveness requires controlling product costs. Developing credible cost

estimate is an important step to achieve competitiveness. Cost Estimating within the industry is still quite ad-hoc and often lacks a robust internal business process.

Cost estimating is not a trivial task, especially when trying to calculate cost at the conceptual design stage where there is limited data available. This limited information is often not utilised due to lack of communication between different stakeholders, which is mainly between commercial (CE-C) and engineering (CE-E) [Roy et. al. (2001a), (2001b)]. The purpose of CE-C in cost estimating is to provide information for decision-making in a top-down fashion. CE-E in cost estimating try to model the design to manufacturing cost using a bottom-up approach to support cost comparisons for different design solutions and manufacturing processes. Effective communication between CE-C and CE-E will enhance the quality of cost estimates and reduce development time for estimation.

Product-costing requires both commercial and engineering specialisations and in order for the cost estimating process to function effectively, it is necessary that these two domains are integrated. It is observed this lack of integration is responsible for weaknesses in internal working practice in many large organisations. This may be due to a lack of cross-disciplinary comprehension and standard terminologies to communication about cost estimation process [Souchoroukov et. al. (2003)]. This paper propose a methodology called FUCE Framework to improve the communication between CE-C and CE-E. The approach allows CE-C to communicate using the functional requirements as the basis for cost estimation, where CE-E works at the detailed design level based on past similar product family for data collection and development of cost estimates. The two activities are then integrated through a function-attribute-product parameter mapping (Souchoroukov (2004).

This paper is structured as follows. In section 2 a review of literature in function based cost estimating and approaches to engineering design is presented. Cost estimating can borrow a lot of ideas from design. In section 3

the paper outlines challenges in improving the interaction between CE-C and CE-E. Section 4 describes the development of FUCE framework to improve the interaction between CE-C and CE-E. Section 5 presents FUCE methodology, a structured approach that involves both the cost estimating groups in the estimating process. The methodology is developed through a detailed case study on Exhaust System of a car. Section 6 applies the FUCE methodology on two other case studies for validation. In section 7 the authors discuss the strength and weaknesses of research methodology and the results obtained from the application of FUCE methodology. Finally the paper ends in section 8 with concluding remarks.

2.0 Related Research

Function-Based Cost Estimating has borrowed ideas from Value Engineering, Value Analysis and Functional Decomposition techniques. Value engineering activity analyses the design of products to find effective ways to achieve all necessary functions and essential characteristics [Elias (1998)]. Value analysis, on the other hand, originated as an engineering design method to evaluate the functionality of products with respect to the cost of making them. It considers functions defined from the customer/ user perspective, as opposed to the designers' perspective [Dieter (1983)].

Quality Function Deployment (QFD) is a recent implementation of the value analysis principles. QFD maps the customer requirements to design attributes, and attempts to quantify how much of the customer requirement is satisfied by each design requirement and at what cost [Johnson and Sapp (1992)]. Functional analysis of systems is not new, Bytheway (1971) developed 'Functional Analysis System Technique (FAST)' as a way to systematically organise and represent the functional relationships of a technical system.

This is still a popular technique in functional analysis. Research in engineering design strategies by Hubka (1980), Love (1986) and Pahl and Beitz (1988) identified the role of a 'function structure' of a technical system early in the design process. Decomposition of a function into sub-functions until the flow

of energy, material and signals through the design are clear is proposed by Pahl and Beitz (1988). Although their approach is important for engineering design, their methodology does not produce repeatable function structures. On the other hand Collins et al. (1976) developed a list of elemental mechanical functions in the analysis of a helicopter part failure. The functions are expressed as a combination of a key word and a preceding adjective and are limited to mechanical design of a helicopter.

Kirschman and Fadel (1998) extended the research by developing a function-based taxonomy of elemental mechanical functions. The basic function groups are motion, control, power/matter and enclose. The approach develops a 'form tree' for the top level product by decomposing the top level functions and by identifying components that can satisfy the requirements at each level. Suh (1990) has developed axiomatic design that links functional requirements with design in a systematic manner. The principle is more suitable for developing a new design rather than dealing with an existing system. In (Mukherjee and Liu, 1997) the authors presented an abstraction for conceptual design by using function-form relation matrices. The relation matrices provide a link between purely geometric representations, and a means to carry out domain-dependent manufacturability evaluations.

Recently, there is an attempt to apply the function-based cost estimating approach for product development (Tsai and Chang, 2004). The research uses QFD to perform the functional analysis and has developed a methodology to predict the cost of a total system based on competitor's costs. Although the research uses a function based approach, it does not address the role of CE-C and CE-E explicitly in the methodology. (Park and Simpson, 2005) have developed a cost estimating approach for Product Families. The research uses an activity based cost estimating approach to predict the production costs.

The study uses a concept of functional hierarchy to define a product family but is only limited to production cost and it is resource intensive. Although there is some research in function based design and in cost estimating areas, it is

observed that there is a lack of a structured cost estimating approach that could improve the interaction between CE-C and CE-E.

3.0 Improving interaction of CE-C and CE-E at the Conceptual Design Stage

CE-C and CE-E have different responsibilities within an organisation [Souchoroukov (2004)]. At conceptual design stage the main responsibility for the CE-C is to prepare a project proposal and check the feasibility of a new product. Their responsibility is to put together the *specifications* of the product and prepare its likely target costs for manufacturing. For that, they need to compare cost estimates with the historical data available to them from previous products made. The information available to CE-C at this stage is quite abstract as it only includes the requirements of the product. The information included in the 'cost information packs' has the form of a list of requirements the product needs to perform and in some cases a conceptual drawing. This is an evolving document which if the project progresses, will include more information until all the required detailed cost estimates are included prior to the manufacturing stage.

During the conceptual design stage the CE-C will have to make some decisions together with the product design team about the specifications of the product and try to create a cost estimate. For example, in the case of a new muffler system, the experts will have to specify what type of car the exhaust system will have to be installed. In most of the cases, this group of people have the expertise to identify what are the specifications of the car but cannot relate how these specifications will affect the product itself and its functions. They lack the engineering knowledge of the CE-E to understand the full effect it will have on the design and cost.

The financial techniques used by CE-C are not always adequate due to their relative simplicity and the target costs produced do not have sufficient back up information that elaborates its values. At this stage the CE-C will request an estimate from the CE-E. This interaction is often very challenging. The

required input for CE-E to prepare a detailed estimate has to have the form of a detailed design, a physical product or the product specifications and detailed manufacturing process. When the CE-E have either a physical part or a detail design, it is relatively easy for them to develop a detailed estimate as most of the required information can be derived from those two mediums. But when the Specifications are provided, CE-E need to make a lot of assumptions [Rush and Roy (2001)] with regards to the way the product will look. The way the product functions will be fulfilled will be affected by the specifications provided.

The types of requests CE-C will ask the CE-E are for example:

- “How much will the exhaust system cost if we increase the engine capacity of the vehicle?” or;
- “How much will it cost to add all-wheel drive to the vehicle? With a small capacity engine or a large one”

At the conceptual design stage this is the type of question a CE-E will receive, *un-quantified request*. The CE-C is not looking for detailed estimates but for an approximate cost in order to be able to make decisions. CE-E, using the bottom-up process will try to acquire more information regarding the product in question and try to use their expert judgement in order to provide the answer. There are a series of problems associated with this approach:

- CE-E make assumptions that are not documented;
- Results are not repeatable;
- Results cannot be explained easily to another cost estimator as they are based on the assumptions of an individual and are not necessarily the most complete.
- The whole process is not systematic.
- In many cases CE-E makes assumptions that are not agreed with engineers, leading to errors in the cost estimate.

While developing a cost estimate CE-C think in terms of the overall car specifications. They often lack knowledge to link the specifications to functions and design. In case of estimating cost for a product they fail to appreciate the impact specifications will make to a design and its functions. If

not communicated clearly and in a systematic fashion, explanation from CE-E is often treated with caution as ‘over estimation’. On the other hand CE-E develops estimates in a detailed manner using design and manufacturing knowledge. They often fail to link design with its overall function in the car. CE-E often criticise CE-C estimates due to the lack of underestimating or appreciation of product and cost issues.

The proposed Function-Based Cost Estimating (FUCE) framework links the specification-based thinking of CE-C with the product functions and then with detailed cost estimates based on similar past designs. The framework will allow CE-E to answer specific questions asked by CE-C. This improved interaction certainly enhances the internal cost estimating practice within the manufacturing industry.

4.0 An overview of the FUCE Framework

The FUCE framework was developed with the help of a large automotive vehicle manufacturer. The framework and detailed methodology development were based on a detailed case study on the Exhaust System of a car. The case study lasted for a period of six months. There were four participants for the research, including a person from the product development department (in this case representing the CE-C) with 12 years of experience in the automotive sector, a CE-E with more than 10 years experience in Cost Estimating, a product engineer associated with Exhaust System for more than 6 years, and a person from Tear-Down being in the company for 8 years. Tear Down is a facility that exists in most of the large automotive manufacturers, this group acquires cars and disassemble them into individual components; this allows engineers within the organisation to investigate how the competitors manufacture similar products and perform benchmark exercises to identify opportunities for design and cost improvements.

The objective of FUCE is to ‘translate the *un-quantified* terminology and the requests associated with the product specifications used by CE-C into a medium that CE-E can process using their resources, and create estimates

that are based on a standardised approach. The framework can be broken down into three basic stages:

Stage 1: Functional Decomposition

In order to analyse how the product is affected by the specifications, the functions of the product need to be analysed. The product is broken down into the basic functions it needs to fulfil using a popular function decomposition technique called FAST [Bytheway (1971)] .

Stage 2: Function and Product Parameter Mapping

The next step is to try and identify what product parameters affect the cost of the product. The objective is to try and answer the questions “How much will it cost me to add this function on my product?” and “How will the specifications affect the cost?” It is important to note that this is the type of questions CE-E are required to answer at conceptual design stage.

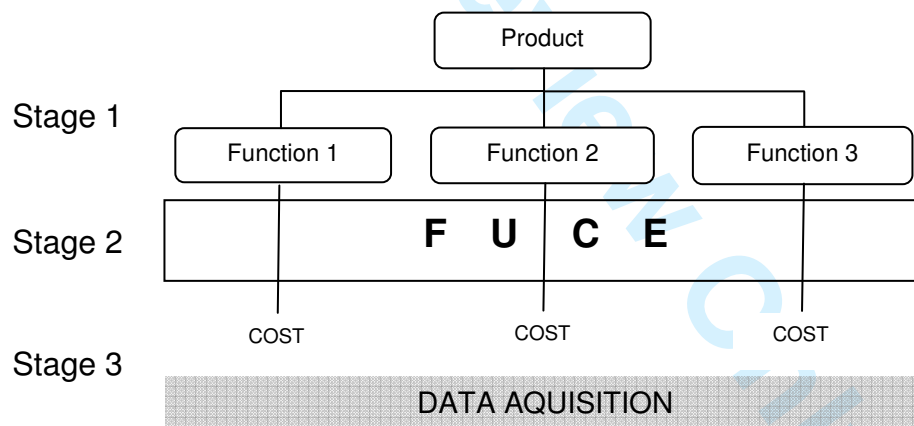


Figure 1: The FUCE Framework

Stage 3: Data Acquisition and Cost Estimating

The third stage relates to the need for data requirements to create a successful cost estimate. Data needs to be collected in relation to previous products made, for example, what material was used in the past, how much of it, what manufacturing process was utilised, etc. Also design attributes need to be collected as they will be used to create relationships between them and cost. Finally, the associated rates (e.g. labour rate) will have to be acquired. Roy et. al. (2004) presents a methodology to develop a detailed cost estimate for a technology intensive product.

The commercial discipline for the majority of their time tries to fulfil customer requirements. CE-C is therefore involved in the functional decomposition part of FUCE framework (stage 1) and also in the mapping exercise between the functions and product parameters (partly stage 2). CE-E on the other hand works off line to collect data and prepares cost estimates based on previous experience (stage 3) and also contributes to the stage 2 mapping. The next section presents a step by step methodology to implement this FUCE framework for a function based cost estimating.

5.0 The FUCE Methodology Development

The first two stages of the FUCE Framework is broken down into step-by-step methodology, the third stage relies on cost estimating practices within the company to produce an estimate appropriate for the component of interest. Figure 2 demonstrates the steps of the FUCE methodology. Initially the methodology is developed conceptually through expert judgement and later on it is applied to a Car Exhaust System case study for initial validation and further development. After the case study, the following steps are finally proposed for the methodology.

Step 1: Define Product Decomposition (PD)

First, the PD of the manufacturing good is created. There are a series of reasons for doing this:

1. If the product has not been estimated before, a breakdown can be provided that will allow the experts to develop an estimate;
2. By providing a PD it is easier for the experts to identify the functions of the product;
3. Another possibility could be that many estimates or designs of similar products already exist within the organisation for this specific commodity. In this case the PD can be used to examine the different types of products and conclude to a generic design that represents most of the products.

In most of the cases there are many similarities between products, once a cost estimate can be associated with ease to the PD then this estimate can be used as the basis for the model development.

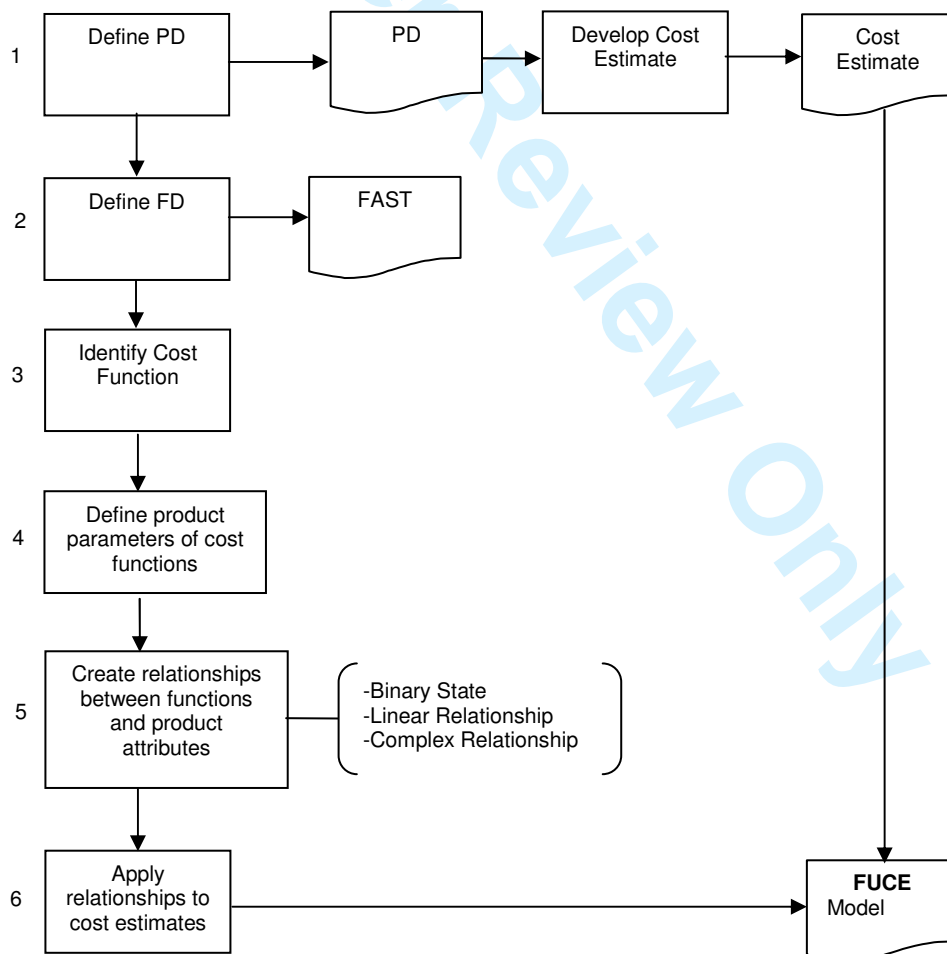


Figure 2: The FUCE Methodology

Step 2: Define Functional Decomposition (FD)

The FD allows the users to associate the functions of the product to the PD and therefore to the cost estimate created. With this approach a link is created with regards to what parts of the product are affected by which functions. The classification will also help the ability to “pick n’ match” functions for the system. For the purpose of this research the authors decided to use Functional-Analysis System techniques (FAST). The FAST technique has long been used in Value Engineering to analyze costs. But, the method can also be useful in Engineering Design. It is proposed that FAST is a powerful design tactic that can be incorporated in any Systematic Design strategy. A FAST diagram showing functional decomposition of a Bulb is presented in Figure 3.

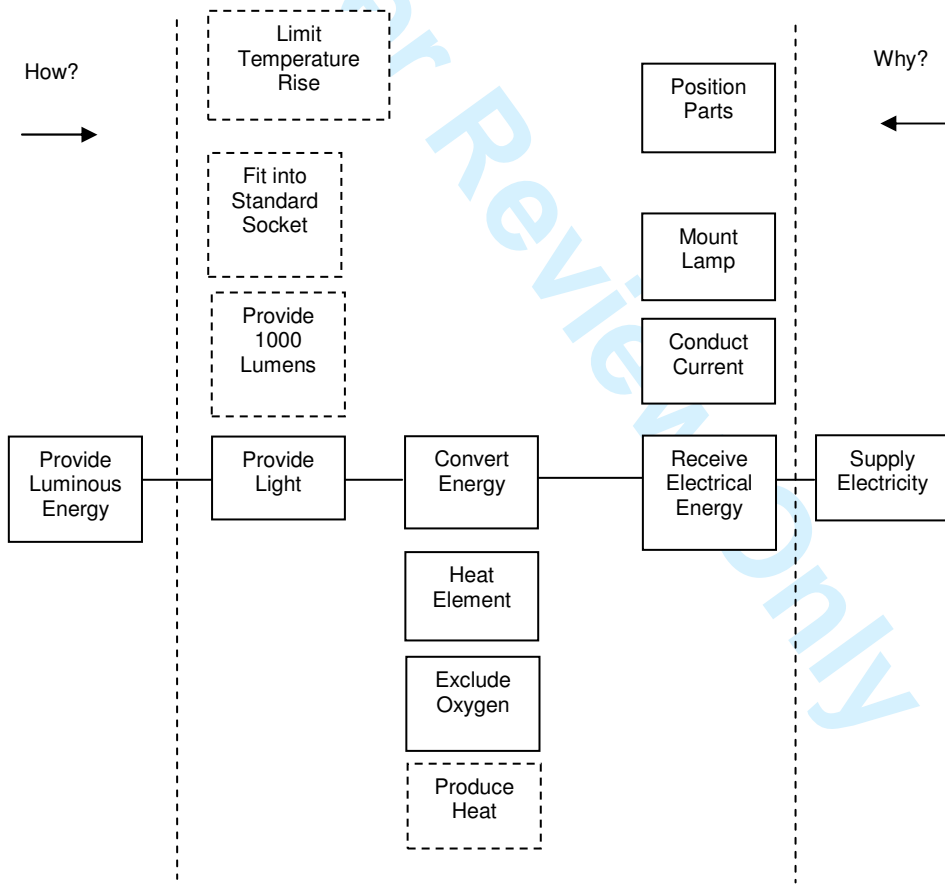


Figure 3: Example of a FAST Diagram-Bulb [SAVE (2001)]

In applying FAST, each function is represented as a verb-noun combination. The verb should be an action verb (hold, protect, rotate, move, control, direct,

etc.), it is the "effect", the "operation" that is performed. Passive or indirect verbs (provide, supply, become, etc.) should be avoided. The verbs describe the "physical effects" that take place within the system. The noun should be descriptive and general; it is the "operand" on which the operation takes place. These nouns can be conveniently identified as some form of material, energy, information, or abstraction (such as reliability).

The functions are classified into basic functions, and secondary (support) functions. The basic functions are those, for which the technical system exists, the basic functions are the functions of the technical system. The secondary functions are all the other functions that are part of the technical system and assist the basic functions. Two arrows are placed at the top of the FAST diagram; one pointing right marked "HOW?", and one pointing left marked "WHY?". The basic and primary supporting functions are selected and placed one above the other to start the FAST diagram, with the basic function uppermost. The remaining functions are arranged to the left or right of functions already on the diagram depending on whether they answer the question "how?" or "why?". If the function is "provide light" the function "convert energy" would go to the right of it because it answers the question "How", the function "provide luminous energy" would go to the left because it answers the question "why" [Figure 3]. This function decomposition methodology is more suitable for domains where functions and how they could be fulfilled are known. The next paragraph discusses a technique to introduce a new function within the FUCE framework.

Adding a New Function

Sometimes it is necessary to incorporate new functions in a product. Traditional function decomposition techniques do not accommodate such cases but in the literature review such a method was reviewed. Kirschman (1996) developed a methodology called Functional Taxonomy and the author suggests that it can be used successfully to identify the physical attributes of novel functions. As it can be seen in Figure 4, the function is broken down into four basic categories: Power, Motion, Control and Enclosure. By identifying or

speculating how this new function can be performed, it is possible to define the product attributes that are required for developing a cost estimate.

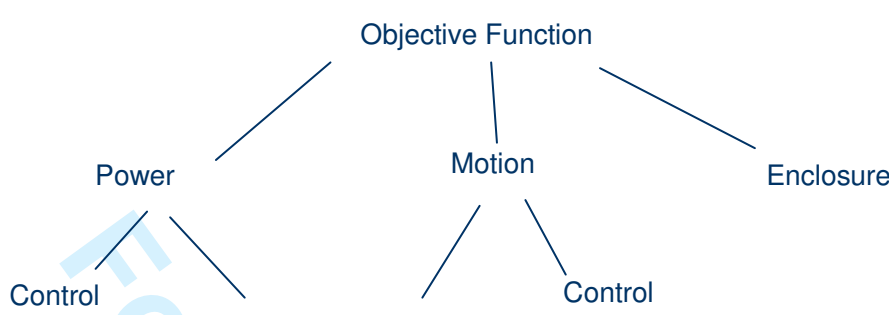


Figure 4: Kirschman's Functional Taxonomy [Kirschman (1996)]

Step 3: Identifying Cost Functions

The next step is to identify the cost functions. Cost functions are those that the experts feel affect the cost of the product the most and they vary. By identifying the cost functions, we identify the variables that are going to be used for the model development. This stage is important because as the experts investigate the functions, they can isolate the ones that they want to represent as a constant value in the cost estimate.

The functions that the engineer chooses to analyse further for cost estimating purposes can be from any, or all of the groups mentioned earlier. The Basic and Task functions are a necessary function for the product. The supporting functions affect the cost too as from their nature and are desired but not necessary.

Step 4: Define Product parameters of cost functions

Once cost functions have been acknowledged, the specifications of the product and its physical attributes that affect those functions are identified. Product parameters that are affected by the attributes are identified from interviews with the engineers and commercial people. Participants include people from product development, tear-down, purchasing, CE-E and CE-C. It is vital to include people with varied background as this creates the opportunity for better results. For example, it is possible that a CE-E can have

a certain understanding of how a function has been fulfilled if he has been estimating cost of a past product. A product engineer who actually develops similar products like the one under investigation or tear-down people who have actually seen competitor's product and experienced different solutions to the same problem, can have a valuable input in identifying those physical attributes.

Step 5: Create relationships between functions and product parameters

Now that the cost functions and the product parameters are established, the next stage is to create a relationship between the two.

Cost functions can be separated into two types. One is binary, you either have it or you don't. The other is related to performance. In this case the experts need to identify how the values of the attributes associated with the function would change.

- If the function is equal to a fixed value, the relationship has to be established between the external parameter in the product attributes.
- If the function has different values, then the relationship is established between those values and the product attributes.

These relationships can either be:

- *Constant*: There is only one value that this function will have. This is usually because that function will represent a "bought out" part or "standard part".
- *Linear*: The relationship may be linear because the design philosophy behind the product has not changed. What will change are the materials used and the size of the product, therefore a linear relationship will be a good a presentation.
- *Complex*: This can be non-linear multi variable relationships.

These relationships are either represented by mathematical equations or by tables. The tables are often created through the knowledge elicitation.

Step 6: Apply relationships to cost estimates

The final step in the methodology is to combine the cost estimate that was decided to be used from Step 1 after the PD was identified and relationships were created. Physical attributes that are not affected by the cost functions identified by the experts will have a constant value, for example, all manufacturing processes regarding the manufacturing of a pipe will have a constant cost associated with it. This will form the basis of the estimating model. Then, wherever an attribute is identified in step 4 will be replaced by the relationship developed (mathematical or table) created during step 5.

5.1 FUCE Case Study-1 Results

The conceptual FUCE methodology was applied on an Exhaust System case study using the four experts mentioned in section 4.0. Once the case study was completed the authors organised a workshop with four experts for initial validation. The actual cost estimating model is developed using MS Excel spreadsheets. Excel was selected because it provided an accessible way for the authors to represent the relationships and the tables he or she would create and then link them to the cost estimate. The availability of an estimate already in Excel within the company also contributed to this decision.

Scenario

The “input” for the CE-E to deal with a request from CE-C will be a sentence with very limited information, which usually will refer to the *specifications* of the product. Although a CE-E has the ability to produce an estimate once a design or a physical part is available; they find it difficult to face such request at the conceptual design stage.

Typical request will include:

How much will the exhaust system cost...:

- a) “...in a small car (class A) with a small engine/1.0 litre?”
- b) “...in a small car with a large engine/2.0 litre?”
- c) “...if we try to improve the life of the component from 2 to 5 years?”

- d) "...if we fit in a large car (class D) a small engine/1.6 and want to have two tailpipes to make it look better"

The authors specified the engine size in the formulation of these questions. It has to be noted that in many cases the request would not even provide such information, it will be just "small engine", "large engine". Following the methodology, the author will try to answer questions a) to d).

Description of an Exhaust System

Figure 5 presents a breakdown of an Exhaust System within a car. The major parts of the system include muffler, the tailpipe, exhaust pipe hanger, catalysts and the exhaust pipe. A full description of the exhaust system is presented in (Souchoroukov, 2004).

The muffler quietens the noise of the exhaust by "muffling" the sound waves created by the opening and closing of the exhaust valves. When an exhaust valve opens, it discharges the burned gases at high pressure into the exhaust pipe, which is at low pressure. This type of action creates sound waves that travel through the flowing gas, moving much faster than the gas itself (up to 1400 m.p.h.), this is what the muffler must silence. It generally does this by converting the sound wave energy into heat by passing the exhaust gas and its accompanying wave pattern, through perforated chambers of varied sizes. Passing into the perforations and reflectors within the chamber forces the sound waves to dissipate their energy.

Data Collection

One of the most important factors to have a successful application of the FUCE framework is the data availability. In this case study, information was gathered using different sources of information, for example, commercial magazines, or internal information to the company. In Table 1 a sample of the relevant data analysed is presented, it includes information like engine capacity, muffler volume, materials used, etc.

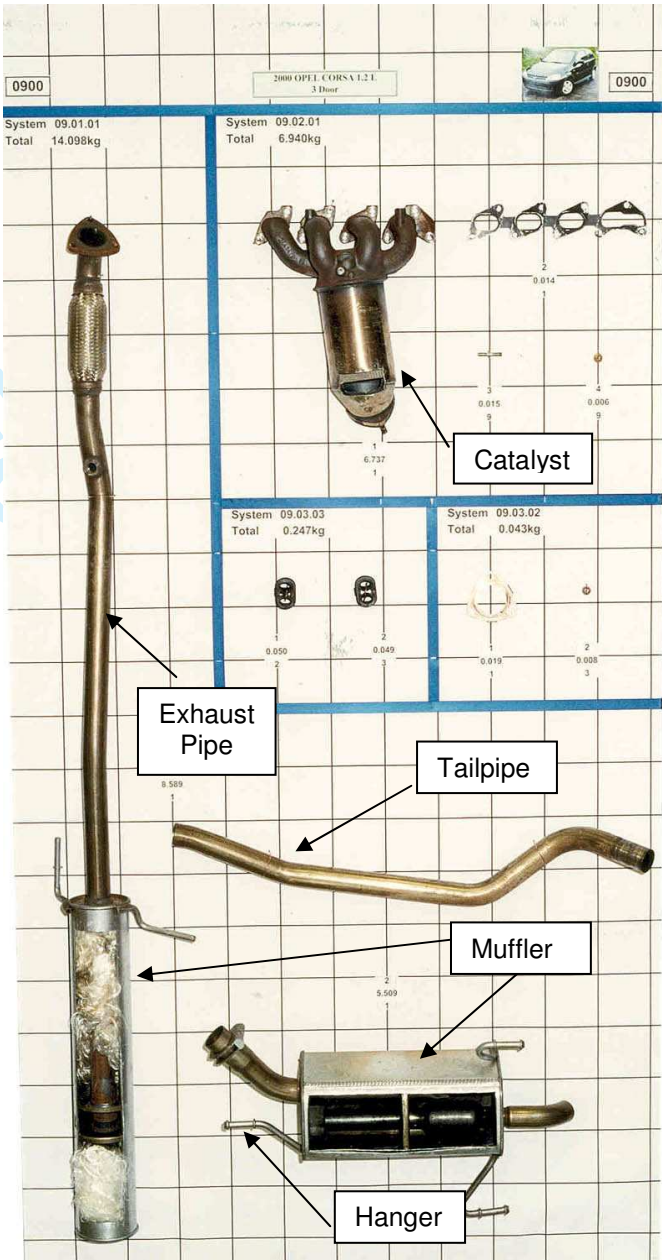


Figure 5: An Exhaust System

It has to be stressed that the analysis did not take into consideration only the sponsor's products but also those of the competition. Thus data was acquired by examining components from tear-down exercises. In this case, the researcher had the opportunity to have an interaction with the physical components and take measurements at first hand.

This type of information is needed in order to create the relationships between the functions and the product parameters.

Table 1: Analysis of information of competitor's muffler systems – Benchmark Summary, Fiesta Rivals Petrol

GENERAL							MUFFLER VOLUME (L)				WEIGHT (KG)			EXTERNAL MATERIALS		
Vehicle	Year	Interpipe	DE	No. of	T/P	T/P	Front	Rear	Total	xESW	Muffler	Muffler	System	Muffler	Muffler	Interpipe
		O/D (mm)	Coupler	Hangers	Visible	Stiffener					Front	Rear	Total	Front	Rear	
GM Corsa 1.0 12v	2000	38	Flex	5	Yes	No	7.1	11.3	18.4	18.4	4.5	5.4	9.9	Ferritic	Ferritic	Austenitic
GM Corsa 1.4 16v	2000	45	Flex	5	Yes	No	5.4	11.3	18.7	11.9	4.4	5.1	9.5	Alum	Alum	Ferritic
Mercedes A 180	1998	41.5	Balljoint	3	No	No	N/A	11.5	11.5	7.2			18		Ferritic	Ferritic
Nissan Micra 1.0	1999	38	Balljoint	5	Yes	No	N/A	5	5	5.0			16		Ferritic	Steel
Peugeot 206 1.1	1998	42	Balljoint	3	Yes	No	N/A	12.6	12.5	11.4			?			
Renault Clio 1.4	1998	47.5	Flex	2	No	No	2.2	11	13.2	9.4			15.6	Alum	Alum	Steel
Skoda Fabia 1.4	2000	45	Flex	5	No	No	4	18	22	15.7	3.4	8.1	11.5	Alum	Alum	Ferritic
Toyota Yaris 1.0	1999	38	Balljoint	4	Yes	No	2.8	9	11.6	11.6			10.65	Austenitic	Austenitic	Austenitic
	Mean Value	42	Mean Value	4			Mean Value		13.9	11.3	Mean Value		12.7			
B2XX 1.3 RoCam	2002	42	Flex	3	No	No	-	12.5	12.5	9.6	N/A	5.95	10.85		Ferritic	Ferritic
B2XX 1.4 Sigma	2002	42	Flex	3	No	No	-	12.5	12.5	8.9	N/A	5.45	10.35		Ferritic	Ferritic
B2XX 1.8 Sigma	2002	45	Flex	4	No	No	3	12.5	12.5	9.7	2.00	5.65	12.35	Ferritic	Ferritic	Ferritic

Define Product Decomposition (PD)

The first step was to identify the PD. This was done by analysing the same type physical part, looking at past estimates and by consultation between the experts. In this case the organisation had already developed a cost estimate for one of the exhaust systems. The objective was to try and create a “basic” detailed cost estimate (a template), an estimate that could be manipulated later using the relationships that would be created. Figure 6 below, demonstrates the PD of a muffler system of a car. The sponsor for the case study uses detailed cost estimating process, and would therefore be the basis for this study.

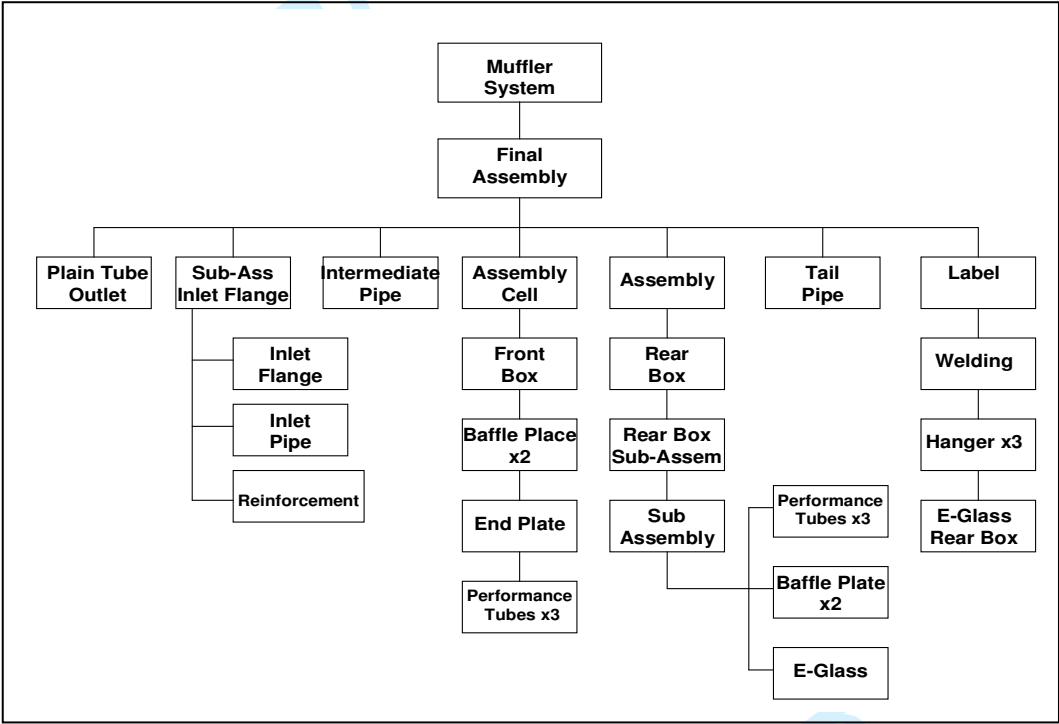


Figure 6: Product Decomposition of a muffler system

Based on all the above an estimate was created. A ‘snapshot’ of that estimate is presented in Figure 7. During the analysis of the data, it was observed that a small number of products were designed with two rear mufflers and two exhausts. This was usually found in big cars or sports cars. Therefore the estimate used had to accommodate for the possibility of two mufflers and two tail pipes. It was decided by the team that a rule will need to be created to make the decision when to use two or one rear muffler.

Define Functional Decomposition

Figure 8 presents the functional decomposition for the Exhaust System. 'Provide Exit (for Gas)' and 'Control Noise' are basic functions whereas 'contain gas' is a secondary function.

Assy	Description	Code	Flag	Mat Usa	Mat Rate	Man Level	LB	G	Lab Mins	Lab Rate	Pieces /Hr	Mat Co	Item C	Comp	Manuf Cost
0	Inlet Stub pipe (50 x 1.5 x 1.5)														
	Part Number: 97BB-5K2														
	INSPECTION	2E+06					AA		0	0.7694	600		0.006	DEM	0.006
	END FINISH (both ends)	7E+06					AB		0	0.8039	300		0.044	DEM	0.044
	END SIZE MACHINE (one)	7E+06				1	AB		0.2	0.8039	300		0.198	DEM	0.198
	CUT AND END FINISH MA	7E+06				1	AB		0.1	0.8039	600		0.106	DEM	0.106
	SUB								0.3			0	0.355	DEM	0.355
0	Inlet Flange			1	1.5							1.5	1.5	DEM	1.5
0	Inlet Pipe														
	Part Number: 97BB-5K2														
	INSPECTION	2E+06					AA		0	0.7694	150		0.026	DEM	0.026
	TACK WELD RINFORCE	7E+06				1	AB		0.1	0.8039	600		0.102	DEM	0.102
	END FINISHING MACHINE	7E+06					AB		0	0.8039	150		0.088	DEM	0.088
	CUTTING MACHINE (snal	7E+06					AB		0	0.8039	150		0.156	DEM	0.156
	AUTO TUBE BENDER (2	7E+06 D				1	AB		0.4	0.8039	150		0.322	DEM	0.322
	CUT AND FINISH MACH	7E+06				1	AB		0.1	0.8039	600		0.106	DEM	0.106
	S/S TUBE 409 50 x 1.5 x			0.5	7.15							3.575	3.575	DEM	3.575
	SUB								0.6			3.575	4.514	DEM	4.514
0	Intermediate Pipe														
	Part Number: 97BB-5K2														
	INSPECTION	2E+06					AA		0	0.7694	55		0.07	DEM	0.07
	END FINISHING MACHINE	7E+06					AB		0	0.8039	55		0.242	DEM	0.242
	END SIZE (Both Ends)	7E+06					AB		0	0.8039	55		0.242	DEM	0.242
	CUTTING MACHINE	7E+06					AB		0	0.8039	55		0.428	DEM	0.428
	AUTO TUBE BENDER (7	7E+06 D				1	AB		1.6	0.8039	38		1.286	DEM	1.286
	CUT AND FINISHING MA	7E+06				1	AB		0.1	0.8039	600		0.106	DEM	0.106
	S/S TUBE 409 50 x 1.5 x			2.48	7.15							17.73	17.73	DEM	17.732
	SUB								1.7			17.73	21.05	DEM	21.046
0	REINFORCEMENT														
	Part Number: 97BB-5K2														
	INSPECTION	2E+06					AA		0	0.7694	600		0.006	DEM	0.006
	END FINISHING MACHINE	7E+06				1	AB		0.1	0.8039	600		0.102	DEM	0.102
	CUT AND FINISHING MA	7E+06				1	AB		0.1	0.8039	600		0.106	DEM	0.106
	S/S TUBE 409 53 X 1.0 X			0.047	5.44							0.256	0.256	DEM	0.256
	SUB								0.2			0.256	0.47	DEM	0.47

Figure 7: Snapshot of muffler estimate

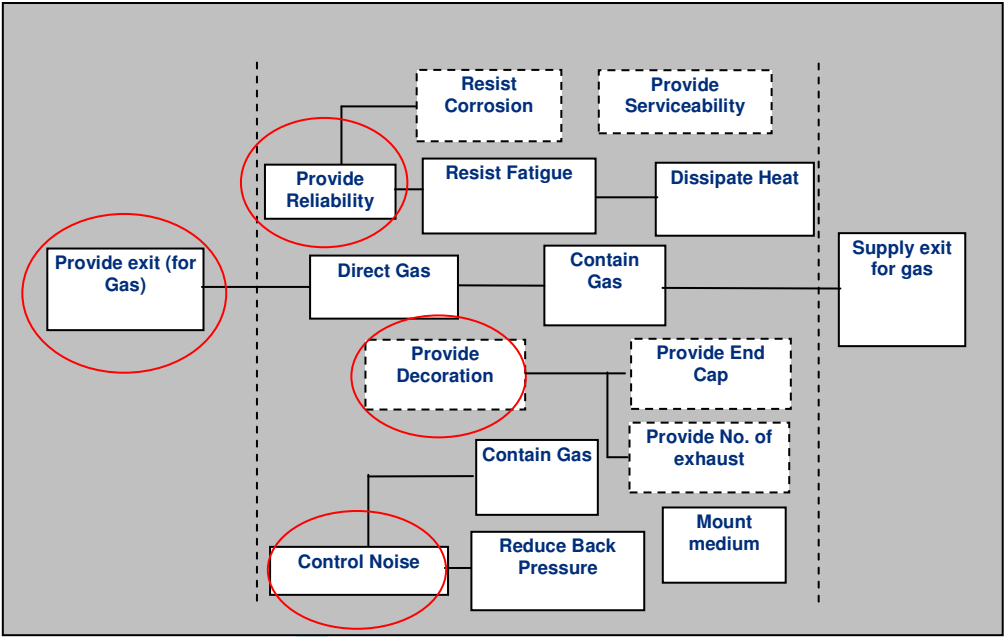


Figure 8: Functional Decomposition of an Exhaust System.
The marked items are the cost functions.

Identify cost functions

These following functions were selected based on expert judgement by the commercial people in the team as the most important and the ones that affect the cost the most. It was then confirmed by the CE-E [Figure 8]:

1. Provide exit
2. Control noise
3. Provide Reliability
4. Provide Decoration

Define Product parameters of cost functions

Expert judgement and domain knowledge is used in identifying the product attributes that affect the cost functions. For example, *control noise* and *provide reliability* functions are affected by the engine size and the lifetime. The product parameters (within the exhaust system) that are affected by the attributes are identified next. A summary of the cost functions and related product parameters are presented in Table 2.

Table 2: Cost Functions and Product Parameters for the Exhaust System

Cost Function	Product Parameters
<i>Provide exit</i>	-Length
<i>Control noise</i>	-Muffler Volume -E-Glass weight -Pipe diameter
<i>Provide Reliability</i>	-Material Properties -Material Thickness
<i>Provide Decoration</i>	-Material Properties -Design Features

Create relationships between functions and product parameters

After the input parameters, the cost functions and the physical attributes were established, the next stage was to create a relationship between them. In case of *control noise*, the decision was to satisfy the functions, the experts did not want to reduce the output of decibels as other parts of the car would make more noise (tyres), and did not want to increase it as it would bridge the legislation limit. On the other hand *provide reliability* could have different values (one year, two years... up to five years). In this case the author needed to identify how the values of the attributes associate with the function would change depending on the specifications. The relationships were either represented by mathematical equations or by tables. They were created through eliciting the knowledge of the expert. A series of data available either from the tear-down department or from the engineers were also analysed in order to create the relationships. Details of the estimate development are reported in (Souchoroukov, 2004). Please note that two other commercial factors that are added to the study are 'country of origin' and 'timeframe' (Figure 9).

These additional commercial factors were added as a result of the validation with engineers and commercial people. The labour rates in different countries and the inflation rates are captured from the experts from their experience. During the development of the relationships, the group agreed that a number of parameters had to be kept constant. All manufacturing costs were kept the same; for example, costs of the manufacturing processes like inspection, finishing, etc. were assumed to be the same for any type of pipe cost estimate that was produced. It did not matter if the pipe was longer or shorter, the inspection and finishing processes would almost be identical.

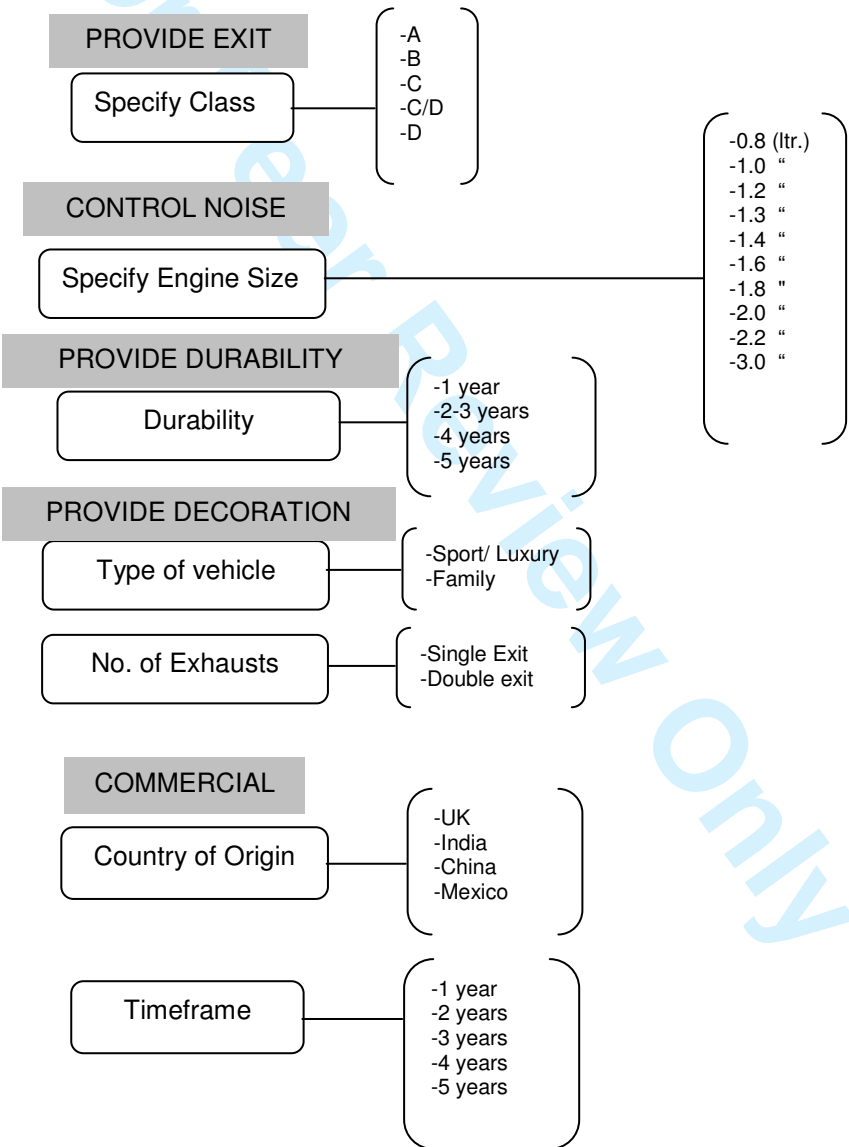


Figure 9: FUCE Inputs for the Exhaust System

Also the number of hangers needed to keep the muffler system attached to the car and the cost of the flanges needed to connect pipes was kept the same for simplicity purposes.

Apply relationships to cost estimate

The relationships created between functions, product attributes and parameters were applied to the cost estimate that was created with the assistance of the PD. A worked example on 'intermediate pipe' is presented in (Souchoroukov, 2004). In the introduction of this case study a list of different request were made. The questions are provided below, followed by an answer. All the estimates are produced using the model created for this case study.

Question a: "How much will the exhaust system cost in a small car (class A) with a small engine/1.0 litre?"

INPUT

Specify Class	A
Specify Engine Size	1.0
Durability	2-3 years
Type of Vehicle	family
No. of Exhaust	1
Country of Origin	UK
Timeframe	1

OUTPUT SUMMARY (Answer)

Item	Cost (£)
Pipes	2.3
Front Muffler	5.5
Rear Muffler 1	8.4
Rear Muffler 2	0
E-Glass	0.82

Assembly Costs	5.8
Other Costs	10.88
Total Piece Cost	33.7

Question b: “How much will the exhaust system cost in a small car with a large engine/2.0 litre?”

INPUT

Specify Class	A
Specify Engine Size	2.0
Durability	2-3 years
Type of Vehicle	family
No. of Exhaust	1
Country of Origin	UK
Timeframe	1

OUTPUT SUMMARY (Answer)

Item	Cost (£)
Pipes	2.9
Front Muffler	5.6
Rear Muffler 1	9.1
Rear Muffler 2	9.1
E-Glass	1.4
Assembly Costs	7.3
Other Costs	9.9
Total Piece Cost	45.3

Question c: “How much will the exhaust system cost if we try to improve the life of the component from 2 to 5 years?”

INPUT

Specify Class	A
Specify Engine Size	1.0
Durability	5 years
Type of Vehicle	family
No. of Exhaust	1
Country of Origin	UK
Timeframe	1

OUTPUT SUMMARY (Answer)

Item	Cost (£)
Pipes	4.5
Front Muffler	8.4
Rear Muffler 1	15.6
Rear Muffler 2	15.6
E-Glass	1.4
Assembly Costs	7.8
Other Costs	9.45
Total Piece Cost	62.75

Question d: How much will the exhaust system cost if we fit in a large executive car (class D) a small engine/1.6 and want to have two luxury tailpipes to make it look better”

INPUT

Specify Class	D
Specify Engine Size	1.6
Durability	2-3 years
Type of Vehicle	luxury
No. of Exhaust	2
Country of Origin	UK
Timeframe	1

OUTPUT SUMMARY (Answer)

Item	Cost (£)
Pipes	10
Front Muffler	0
Rear Muffler 1	9.5
Rear Muffler 2	0
E-Glass	1.1
Assembly Costs	5.7
Other Costs	11
Total Piece Cost	37.3

Validation of the FUCE methodology and results

The FUCE methodology and the Exhaust System case study results were validated using a workshop. In addition to the four cost estimators who took part in the FUCE development stage, two more cost estimators, one CE-E (with 5 years of experience) and one CE-C (with 2 years of experience) were invited to the workshop to participate in a presentation of the methodology and to use the final model created. The model was also validated with another automotive organisation. Two other cost estimators, one CE-C (7 years experience) and one CE-E (8 years experience) reviewed the model offline.

The areas of interest that the authors asked the participant to comment on were:

- *Performance* (how long does it take to use it and how much data is needed)
- *Accuracy*
- *Ease of Use*
- *Relevance* (Could it be used day-to-day?)
- *Completeness* (Does it cover everything or not)
- *Ease of Adoption*
- *Transferability* (Could it work in every system, e.g. electronics)
- *Improving interaction of CE-C and CE-E*

The following are sample qualitative evidence of the responses received against the topics mentioned above.

Interaction of CE-C and CE-E

"By following the framework and creating the exhaust muffler model, we have created in effect a translator in place between commercial (CE-C) and engineering (CE-E). By that I mean we have a system that manages to use a small amount of input information to provide a detailed estimate. CE-C can respond to requests by receiving a very small amount of information indeed. Now we can provide them an estimate for the muffler within a couple of minutes. Before it would take at least a couple of days as we had to go and find some more information about their request"

"I believe the great benefit of FUCE is not only the resultant model of the commodity that we analyse but the methodology and the way both groups (CE-C and CE-E) interact in order to develop that model. I cannot think of a circumstance that I spend so much time together with commercial people!"

Qualitative analysis of the validation results resulted in few changes in the framework and in the specific case study. As a result of the validation the commercial inputs were added to the Exhaust System case study, and labour rates are changed to reflect more current market conditions. Overall, following are the summary of observations from the validation:

- All the experts agreed that the framework is applicable to other mechanical parts of the vehicle;
- The cost estimate that was produced is company specific but the framework is generic within the automotive environment;
- The framework once implemented will improve interaction between CE-C and CE-E and thus improve the internal practice of CE.

FUCE methodology was applied to another automotive case study to further validate the generality of the methodology and to one aerospace case study in order to check it's relevance to other sectors.

The next section presents only results of these case studies, for full details please refer to (Souchoroukov, 2004).

6.0 Further validation of the FUCE methodology

6.1 Case Study-2: Sideshafts of a car

The Sideshafts case study was developed with the assistance of a big car manufacturer, specialising in luxury vehicles. For the purpose of the case study, two experts were involved, one CE-E with 6 years of experience, and one CE-C with 13 years of experience. The case study was completed over a period of three months. A supplier of the commodity and an engineer from the product development team of the automotive company-with considerable experience of over 10 years each-were consulted for refining the model. The study used a detailed cost estimate developed after the product decomposition stage using past examples. After the completion, the results were presented to the same group of experts for validation and suggestions.

Scenarios

The typical scenario tried to address in this case again relates to the internal interaction of CE-C and CE-E. At the development stage of a car, CE-C will require a cost target for the Sideshafts component and they will ask a CE-E to provide an estimate *based on different vehicle specifications*. Figure 10 shows a typical Sideshafts assembly with 'G.I.' or 'Glaenzer Intérieur' and 'G.E.' or 'Glaenzer Extérieur' joints. The types of questions they will have to answer, for example, are "How much will the Sideshafts cost for a...:

- i. ...medium, front-wheel drive (FWD) car"
- ii. ...large luxury, rear-wheel (RWD) car?"
- iii. ...sports utility vehicle (SUV) with all wheel drive (AWD)?"

The CE-E can easily produce an estimate when they have a design or the physical part, but when the available information is so vague this is a problem. It is very likely that if you get a CE-E with 20 years of experience to produce

an estimate, he will provide a cost very different from an estimator with 5 years of experience. The main reason for that will be the different assumptions made during the creation of the estimate. Commercial people would have difficulty understanding how the specifications affect the product under investigation and why the costs change. The objective of this study was to develop a cost estimating model that would have to provide answers to questions i, ii, and iii.

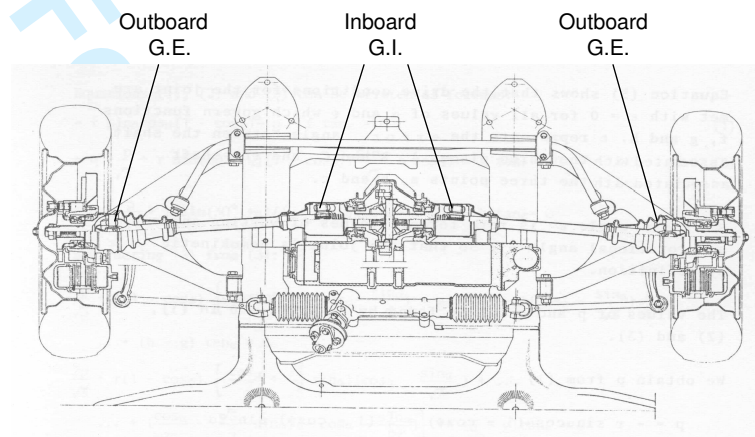


Figure 10: Sideshafts with G.I. and G.E. Joints

Results and validation

After the analysis of the cost functions, the *Torque* was identified as an input to the model; therefore all the questions identified earlier had to be rephrased to include that input (Figure 11). The types of questions expert need to answer are, for example, “How much will the Sideshafts cost for a...:

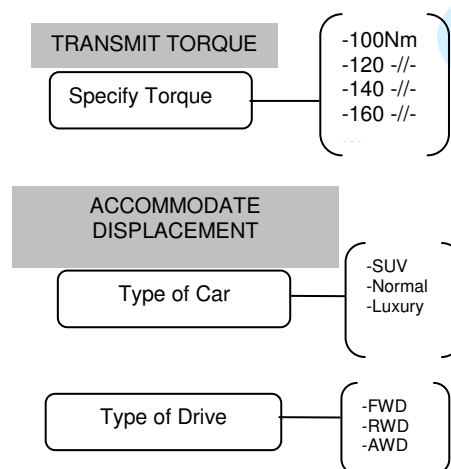


Figure 11: FUCE Inputs for the Sideshafts case study

i)....medium, front-wheel drive (FWD) car, with a 150Nm torque?"

INPUT

Specify Torque	150
Type of Car	Normal
Type of Drive	FWD

OUTPUT

Item	Cost (£)
Connecting Shaft	2.8
I/B Joint	11.2
O/B Joint	10.2
Assembly Costs	7.5
Total Cost	31.7

ii)....large luxury, rear-wheel (RWD) car with 240Nm torque?"

INPUT

Specify Torque	240
Type of Car	Luxury
Type of Drive	RWD

OUTPUT

Item	Cost (£)
Connecting Shaft	2.8
I/B Joint	11.2
O/B Joint	12.7
Assembly Costs	7.5
Total Cost	34.2

iii)....sports utility vehicle (SUV) with all wheel drive (AWD) and 310Nm torque?"

INPUT

Specify Torque	310
Type of Car	SUV
Type of Drive	AWD

OUTPUT

Item	Cost (£)
Connecting Shaft	2.8
I/B Joint	13.2
O/B Joint	14.75
Assembly Costs	7.5
Total Cost	38.25

Summary of validation feedback are as follows:

- ◆ Both the experts involved in the case study agreed that the FUCE framework offered a systematic approach in matching the specifications requirements for the car with the requirements of the sideshafts. As a result a cost estimate was produced that was agreed by both commercial and engineering parties.
- ◆ The methodology involved both groups of CE, as a result the experts commented in a positive way about the 'knowledge exchange' that occurred during those meetings between the two groups.
- ◆ All the participants agreed that the model could be applied in other hardware automotive parts.

6.2 Case Study-3: Vertical Tail Plane

This case study was developed with the assistance of a large aircraft manufacturer. A group of three people were involved, each one of them having experience of more than 20 years. One was a CE-C, one CE-E and one Product Engineer. Again, as in the previous study, work constraints limited the time available for the work and the sessions for the study had to be extended over a period of five months (in-parallel with case study-2). In total 7 half-day meetings were held.

Please note that the data presented in this case study is not real, this is necessary to comply with the confidentiality agreement.

Scenario

The product under study was the vertical tail plane (VTP). The experts described that the interaction between the different groups of people involved in the commodity was not very good. CE-C were producing estimates based on parametric models without a clear understanding of what actually was changing in the product as such. CE-E were trying to analyse the cost estimates but there was no detailed cost estimate from past products that could be utilised. A comment made by all the experts was that there was no transparency within CE. The objective of this case study was to identify the cost of the vertical tail plane at the conceptual design stage and improve the internal communication of CE.

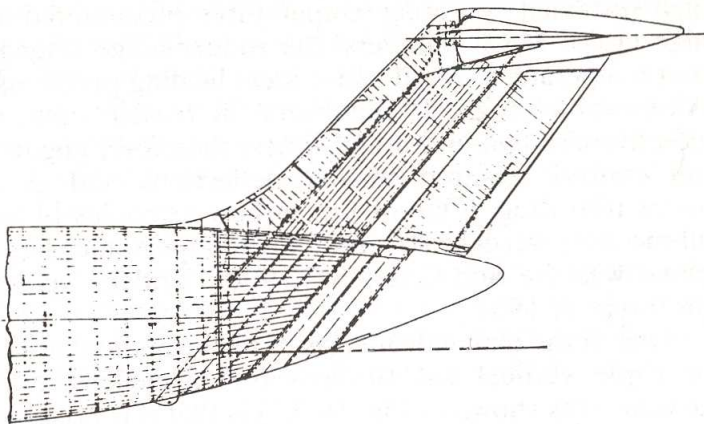


Figure 12: Vertical stabiliser structure arrangements [Niu (1988)]

A large transport aircraft will need to be stable to gently position the aircraft, fly in emergency (engine-out) conditions and react to side winds. The vertical stabiliser box is a two or multi-spar structure with cover panels. The root of the box is fixed at the aft fuselage juncture with fittings or splices or the box spars terminate on bulkheads in the aft fuselage that are canted into the plane of the spars as show in Figure 12, thus transmitting the fin loads directly into the fuselage structure and avoiding the fatigue-critical structural splices. It is important to note that the sizing of the fin is specified by the aerodynamic requirements of the plane.

Indeed the sizing was considered by the CE experts to be the most important “input” for their cost estimating process for this commodity in terms of the *specifications*. Cost estimators were given the size of the VTP and they had to identify how much it will cost. It has to be noted that the VTP does not change in every aircraft manufactured, consequently, for this case study the team decided to develop VTP cost estimates for three different sizes, each corresponding to a different class-size aircraft.

Results and validation

Following are examples of the cost of the VTP Box for small, medium and large VTP assembly.

i) Cost of Box for a Small VTP

		Plane1		
INPUT				
Small VTP				
Area	qm	22		
Height	m	5.9		
weight	kg	470		
OUTPUT				
Main Component		kg	€	€/kg
VTP Total		331	153,076	463
VTP Box		330.8	153,076	463
Shells		250	41540	166
Spars		42	38976	928
Ribs		25.4	51310	2,020
Fittings		13.4	21250	1,586

ii) Cost of Box for a Medium VTP

		Plane2		
	INPUT			
	Medium VTP			
Area	qm	45		
Height	m	8.3		
weight	kg	1,180		
OUTPUT				
Main Component		kg	€	€/kg
VTP Total		578	275,537	477
VTP Box		577.8	275,537	477
Shells		436	69000	158
Spars		74.2	65472	882
Ribs		47.5	98065	2,065
Fittings		20.1	43000	2,139

iii) Cost of Box for a Large VTP

		Plane3		
Large VTP				
Area	qm	53		
Height	m	9.3		
weight	kg	1,440		
Main Component		kg	€	€/kg
VTP Total		676	381,773	565
VTP Box		675.722	381,773	565
Shells		504.8	85643	170
Spars		81.522	132159	1,621
Ribs		62.1	115379	1,858
Fittings		27.3	48592	1,780

Under normal conditions the cost estimators in the company would prepare estimates that look like the three ones described above. By following the FUCE methodology though, the experts have identified a series of parameters that change with regards to the size of the fin. For example, the cost per kilo for the “Spars” is (from the results above):

- Small: 928 €/kg
- Medium: 882 €/kg
- Large: 1,621 €/kg

Before the analysis of the case study, it was not clear to CE-C why the costs will vary. Also product engineers were not able to identify where the extra cost comes from. During the case study a series of assumptions were documented and relationships were created. For example, the difference of the ‘spars’ cost estimate between a medium and a large spar was attributed to certain special design decisions related to the function ‘*protect against impact*’. Before only the person who made the assumption could understand this relationship, now with the application of FUCE, the assumptions were communicated to both CE-E and CE-C. As a result, there is a much clearer understanding of the product and the changes that are required for each type of aircraft. After the results were obtained from the three sized VTP, the total cost estimates were close to the ones observed with the traditional parametric tools. The same CE-C and CE-E experts were involved in the validation.

The authors wanted to validate if the framework will improve the interaction between CE-C and CE-E. A summary of the key feedback from the validation is as follows:

- ◆ Both experts agreed that the interaction and understanding between CE-C and CE-E was improved due to FUCE. Now they could understand what was the reason behind certain changes to the cost estimates;
- ◆ Both experts participating in the study agreed that the FUCE framework would be better utilised with the application of detailed bottom-up estimating. Although the estimates produced were relatively accurate, they were produced using the same method utilised in the company and therefore there was no extra advantage offered in the FUCE approach.
- ◆ Because the methodology involved both groups of CE, the experts commented in a positive way about the 'knowledge exchange' that occurred during those meetings between the two groups.
- ◆ Both experts agreed that the model could be applied in most of the hardware products in their industry.
- ◆ Both experts agreed that a more important consideration should be given to the development of detailed estimates in the aerospace industry. The benefits would include a lot more understanding of the costs and the FUCE framework could be applied with potentially the same benefits as in the automotive industry. The biggest limitation to this approach would be the time needed in order to develop the estimates.

7.0 Discussion and Conclusions

A function-based cost estimating framework is proposed to improve the interaction between CE-C and CE-E. A detailed FUCE methodology is presented to estimate cost of a product at the conceptual stage. The methodology is qualitatively validated through two automotive case studies and one aerospace case study. The methodology is dependent on developing a product decomposition structure that determines a cost estimate. The relationships between functions and product parameters are then applied to

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the cost estimate. The level of the decomposition should match the cost estimating requirements for the industry and availability of data. For example, automotive industry expects a detailed estimate (based on previous example) even at the early stage of a product development, whereas aerospace industry uses parametric cost estimating as a common practice. Once the right level of the product decomposition is completed, that could be the basis of other activities such as sourcing decision making. The two types of case studies in automotive and aerospace industries show that the methodology can work with different types of cost estimating approaches and different levels of product decomposition.

The use human experts as the source of knowledge during the methodology development and the case studies could bring bias into the study. The authors are aware of the challenge and have used triangulation of multiple expert views as a way to reduce the bias. The experts agreed that the cost models created using FUCE methodology could be used for a considerable length of time unchanged. That allowed CE-C to create cost estimates with regards to target cost and feasibility studies in a matter of minutes with all the correct assumptions made, instead of the much longer periods required before. On the other hand, CE-Es were satisfied that they had the 'ownership of the estimate and the rules and assumptions were primarily created by them, therefore the cost should be in accordance to their expectations.

Overall, all the experts agreed that FUCE methodology minimised the time necessary to create cost estimates at the conceptual design stage where both CE-C and CE-E had to collaborate. But, the methodology requires a considerable amount of commitment from all participants for the creation of the model in the first place. FUCE methodology captures previous experience, and therefore needs to be updated with change in functional requirements and technological innovations. Companies need to define an update frequency based on the type of products. It is also observed that the FUCE methodology is more suitable for relative smaller assemblies or large components.

This methodology could not be applied to say for example, to the whole car as the number of functions associated with it would so large that would make the model unworkable. It is also observed that a facilitator needs to explain the methodology to the user first and show one example step by step to demonstrate the different steps to be taken. This is certainly an additional cost for the FUCE implementation. On-line training material on how to use FUCE could reduce this dependence on the facilitator and thus reduce the cost.

In future, it would be necessary to extend the FUCE framework to involve suppliers at the early stage of the design process. Like CE-E, suppliers should be able to provide their estimates and communicate with CE-C team.

Conclusions from the research presented in this paper can be summarised as follows:

1. It is possible to improve the interaction between CE-C and CE-E at the conceptual design stage through a structured function-based cost estimating framework, where both groups get involved and contribute.
2. A FUCE methodology is developed that captures functional decomposition knowledge of CE-C and product parameters and related costs knowledge from CE-E. The methodology links the two types of knowledge through a function-attribute-parameter mapping. The methodology utilises previous cost estimates to reduce the cost model development time for a similar product.
3. The FUCE methodology is validated within the automotive and aerospace environments. The methodology shows more benefit with a detailed cost estimating approach from the CE-E after the product decomposition stage.

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