ENTERPRISE WIDE COST MODELING: A SYSTEMS ENGINEERING PERSPECTIVE

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In the present research the problem of Enterprise wide cost modeling is approached from a systems engineering standpoint. What this does is to use each stage of product life cycle to obtain useful information that helps in estimating the cost of the system. Once a generic framework is developed for estimating the core cost, layers of other factors that affect the cost are applied to the core cost such as risk and uncertainty, maintainability, supply-chain and socio-economic conditions. The cost model is expanded to accommodate a product domain ranging from a simple object to a system in the following hierarchy: System, Product, Assembly, Object. The cost model caters to the needs of cost estimation at every stage of the life cycle and for every kind of product, big or small, simple or complex. New process selection tools have been added to the field of cost estimation which suggests the user with applicable processes given the material and production quantity. Attributes such as materials, fabrication processes etc… are ontology based. This enables a generic category to branch into more and more specialized categories with each step. This is very useful since, in the preliminary stages of cost estimation, not much information is available as to what exact material or process is used. In such a case data pertaining to a more generalized material or process can be used.

1. INTRODUCTION

No large project can be undertaken without some form of systems engineering applied in one or more stages of its life cycle. And estimating the cost of a system at the conceptual stage should not be any different. Here a framework is proposed to estimate the cost of systems using systems engineering perspective. In this framework an algorithm is developed that can be applied repeatedly at each level of the hierarchy to obtain the cost of a system. The framework as a result applies to the entire hierarchy: system, sub-systems, assemblies and components. The hierarchy is shown below

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System
Sub-system/Product
Assembly
Part/Object

The generic form of the cost model is parametric. As required in all parametric models, it is assumed that there are precedents available for the product being designed and whose cost is being estimated. The new system whose cost is to be estimated will be referred to as the Target System throughout the rest of the discussion. The Target System may have additional functions besides the ones available in the precedents referred to as Model Systems here. Once the core cost is estimated layers of risk and uncertainty, maintainability and reliability and other Life cycle cost aspects are applied. This type of analysis is very useful in the initial stage of product design where detailed information about the various sub-systems and components is not known yet.

The terms in the hierarchy mentioned above need some clarification in the context of this paper since the terms can be used subjectively. A system here refers to any assemblage of smaller units that perform one or more functions. A sub-system in our context is treated similar to a system, where by it performs one or more functions. It could sometimes be bought from vendors and modified or used in as-is condition. It can also be referred to as product. An example could be an actuator, a motor etc. As explained above, these can also be treated as systems when there is no other unit in the hierarchy. An assembly is, as the name suggests, an assemblage of components. The difference between a sub-system and an assembly is that the functionality an assembly provides changes with the context. Most of the times, they don't have a specific name. For example, it can be a weldment of two or more bars acting as a support for a structure. And mostly these are custom made. A part or an object is the smallest of all the units. These too are mostly custom made. They can be as simple as a bracket or a dowel pin. The differences in the elements of the hierarchy come from cost drivers. The cost drivers of a system and a sub-system come from functional and physical attributes where as for assemblies it is the assembly time and penalties. At part level the cost drivers are the machining time and the setup or preparation time.

2. SYSTEM DEFINITION

A system is an assemblage or combination of elements or parts forming a complex or unitary whole [1].

System = Sub-sys + assembly + parts +….

The diagram in figure 1 below shows the structure of a system in terms of sub-systems, assemblies, parts and interfaces. Note that the sub-systems and other constituents of the system need not be arranged or assembled in the same order as shown in the diagram. The diagram merely shows the constituents of a system.

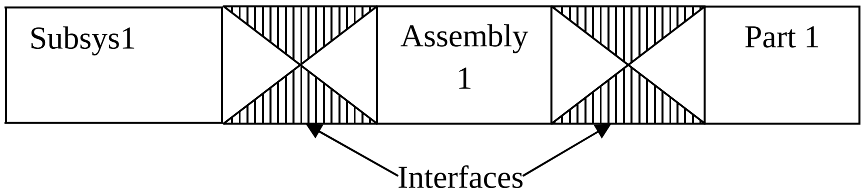

Figure 1. Typical constituents of a System

3. METHODOLOGY AT SYSTEMS LEVEL

A system as discussed above consists of sub-systems, assemblies and objects. The process of estimating cost of a system requires building the entire system but only on paper. The systems engineering process at the conceptual stage of a system development begins with analyzing the needs. What is the need of the system? The stakeholder who generally is the end customer answers this crucial question about the need. The need is generally expressed in plain non-technical terms. For example: The aircraft needs to fly fast, should have long range etc. Once the needs of the system are identified the needs are converted to technical performance measures (TPMs) and compared with the most likely solution. The solution is an existing system that will accomplish the needs. This is called system feasibility analysis. Followed by the feasibility study is the requirements analysis, which determines as to how the tasks required by the system can be accomplished. One of the ways of requirements analysis is the work breakdown structure and functional allocation. In this the functions of the system are broken down to smaller tasks and sub-systems are assigned to each of the smaller tasks.

In the framework proposed in this paper, cost estimation starts from the top level as mentioned above in the systems engineering procedure. The system-needs are converted to TPMs and a feasibility analysis is carried out to see if there are any precedent systems. The precedent systems will be called Model Systems throughout our discussion in this paper and the system being built and whose cost is being estimated will be called Target system. A set of systems which match closely with the demands of the customer are listed. This list is a broader list which needs to be refined. For example if a new transportation mode is being developed and its cost needs to be estimated then the estimator first finds all the likely systems which provide the same functionality asked by the customer. In this example some of the results of the feasibility analysis may be train, planes, cars, vans, SUVs, trucks, busses etc. The conceptual design stage is a critical stage since decisions made here determine the type, technology and cost of the system. The figure 2 below shows the processes involved at the conceptual design stage [1].

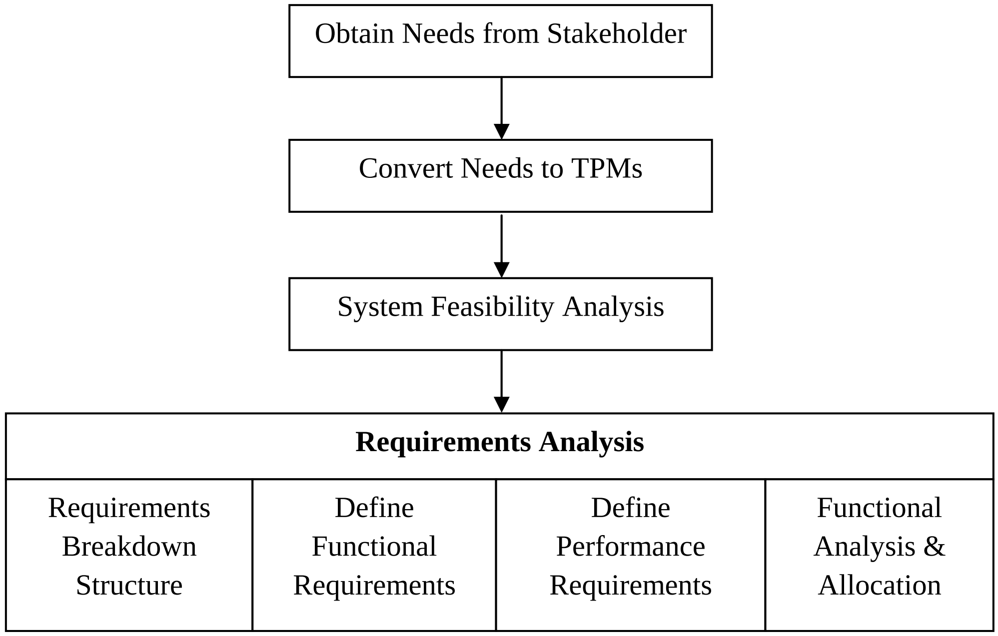

Figure 2. Typical Systems Engineering Process

System Level Requirements Analysis can be broken down into four main tasks

1. Requirements Breakdown Structure: This is similar to work breakdown structure
2. Defining Functional Requirements: If a system is not readily available as discussed above to meet the need of the customer, functions necessary to meet the needs, goals and objectives of the customer are obtained here. The requirements are related to functions (operations), maintenance and human factors.
3. Defining Performance Requirements: This simply answers the question: "How well should the system perform?"
4. Functional analysis & Allocation: The system level functions obtained from the steps above are allocated to sub-systems of the system performing them.

The intent is to find Model system whose functions match close to that of the target system's. The method of dealing with differences in functions is described later in this paper. Table 1 below is a selection process, to identify which model systems, have almost the same functionalities as the target system. The first column shows the functionalities (F_1, F_2, $F_3 \ldots F_n$) in the target system or the functionalities that are required. The subsequent columns represent if the candidate or model systems possess the functionalities with an 'X'.

Target	**Model 1**	**Model 2**	**Model 3**	**Model 4**	**Model i**
F1	X	X	X	X	X
F2	X	X		X	
F3	X		X	X	X
F4		X	X		
.	X		X	X	X
.		X			
.	X	X	X	X	X
Fn		X		X	X

Table 1 Comparing Models to target

In order to find which models most closely resemble the Target unit another matrix is derived in table 2. In this new matrix the Target functions (F_1, F_2, $F_3 \ldots F_n$) are listed in decreasing order of preference.

	Target	**Model1**	**Model2**	**Model3**	**Model4**	**Model i**
TPM Metrics Comparison	F1	2	3	5	3	1
	F2	3	8		7	
	F3	1		7	4	6
	F4		3	9		
	.	6		5	6	4
	.		4			
	.	6	5	3	4	6
	.		5		3	8
	Fn	8		4		2
	SUM→	26	28	33	27	27

Table 2 Weighted Ranking of the Models

Table 2 is a feasibility analysis of various system level alternatives. A ranking procedure is applied to these alternatives to come up with the most suitable solution to the customer needs.

Each model system is rated for each function of the Target. The rating is based on which Model's metric for that function best matches the metric of the Target. The better the metrics compare the higher the ranking. The ranking is on a scale of 1 to 10. Weights are allotted to each function based on its importance once the weights are established the rank of the TPM Metric is multiplied with the weight. All the weighted rankings of each Model are summed. If the sum of a particular model is much lower than the average sum then it can be concluded that the model does not belong to the family of the models that are similar to the target.

With the net score there are a few options in choosing the model system.
Option 1: The model system, which has the highest sum, as described above is the prime model system. A prime model system is one, which contributes the most in terms of cost estimation and resembles the target system the most.
Option 2: The system, which scores the highest on a particular functionality, become the model systems.
In the first option since the prime model system is the closest to the target system among all existing systems, the cost of the prime model system is a good approximation (starting point) for calculating the cost of the target system. In the second option however a solution is picked due to a certain key function. Therefore sub-systems, which provide other functionalities, would have to be designed and made compatible to the main system so the cost of this model system may not be a good starting point. This option might be useful if the major part of the cost of the model system comes from that particular function.

By the end of the exercise above a model system is obtained which closely matches the target system in terms of functionality. If a certain function that the target system has is not present in the model systems its cost is analyzed separately and added to the cost of the target system.

3.1 Repeatability of the Framework

As mentioned above functions not found in the model system are accounted for separately. Figure 3 indicates the recursive nature of the cost estimation process.

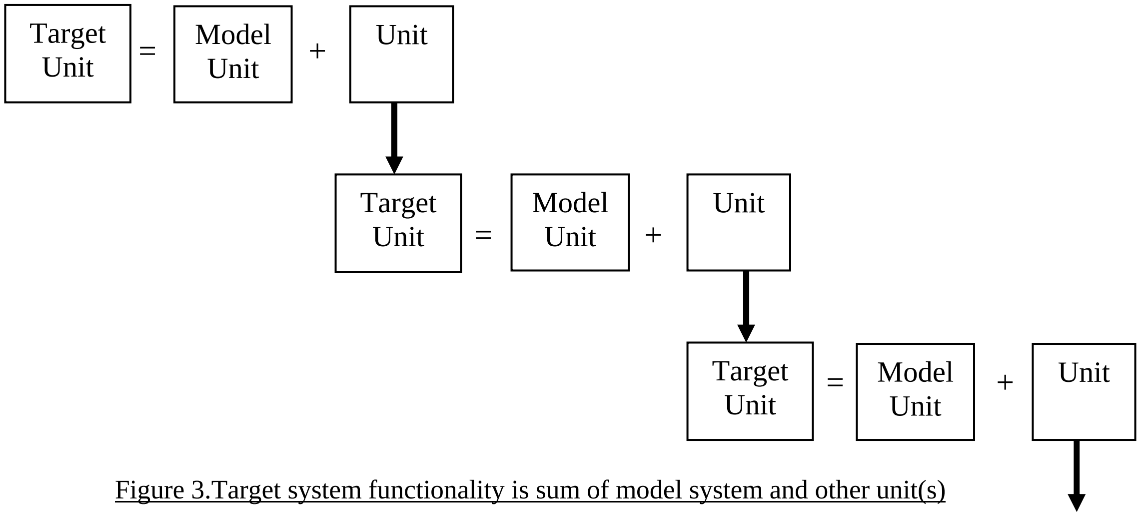

Figure 3.Target system functionality is sum of model system and other unit(s)

In the context of this paper the word unit is used to refer to either a system or a sub-system or an assembly or an object. The representation above means that the cost of the target Unit is obtained from the cost of the model unit, and in order to account for the functionalities missing in the model unit, a separate cost of the unit which provides this functionality is calculated and added to the cost of the Target unit. For example, if the cost of a system is being estimated and a particular model system has all functionalities except a few of the target system's then these missing functionalities are provided by a sub-system whose cost is calculated separately and added to the cost of the target system. This is a repeatable process, which means if the sub-system has a precedent model-sub-system, which offers the functionalities of the target sub-system except a few then these functionalities are looked for either in another unit, which can be either an assembly or an object or a new sub-system.

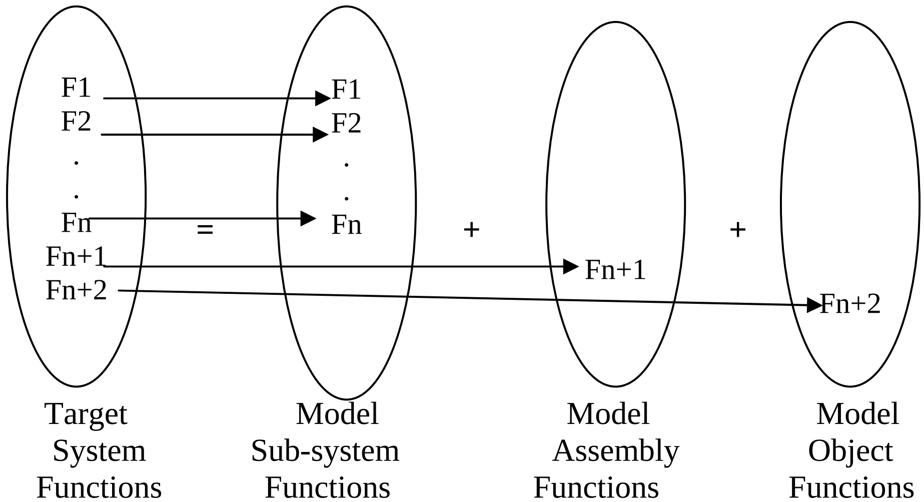

Figure 4.Target system functionality is sum of model system and other unit(s)

Remember, that anytime we need to estimate a sub-system separately we need to make sure it can interface with the main system. If a new interface needs to be designed then its cost must also be taken into account. An interface is also treated as a unit, which means the interface can be a system or sub-system or an assembly or an object.

4. MATH MODEL

What we have seen above is the implementation of systems engineering concepts. A top down break down of system-level functions is done. First the voice of the customer is translated into functional requirements, which are then translated into TPM Metrics. A feasibility study is conducted to see which systems closely match the requirements of the customer.

Once the model system is known several samples of such models are collected. The samples provide data such as functional attributes, physical attributes, reliability attributes and cost. The data can be arranged in several forms depending on what type of math model is required. But before that some basic analysis needs to be performed on the data as shown in the section 4.1.

4.1 Correlation

In order to figure out how each function affects other functions, physical characteristics of the system and also the cost of the system, a correlation matrix is setup. A sample is shown in figure 5. The correlation plots are obtained by plotting each attribute against other attributes. A random spread indicates that there is no interdependence between the attributes. The cost estimator will look at these plots to make sure that the independent variables are not highly correlated [6]. Such cost drivers can be removed. In the cost matrix in the equation-1 it should be noted that the cost of the model systems is adjusted for the year the estimation is made and also adjusted for production quantity. This is called normalization.

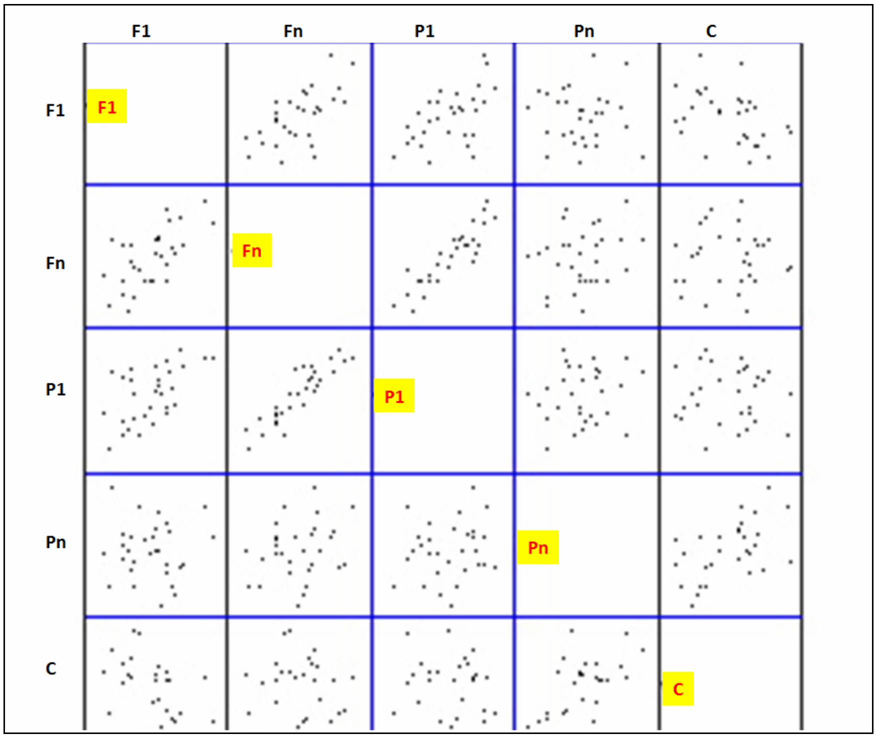

Figure 5.Sample showing correlation between functions and cost

Once the data is overviewed and massaged it can be setup to give the cost coefficients. This can be done in several ways one of which is shown in figure 6.

$$\left\{\begin{matrix} F^{1}_{1} & F^{1}_{2\ldots\ldots} & P^{1}_{1} & P^{1}_{2\ldots\ldots} & R^{1}_{1} & R^{1}_{2\ldots\ldots} \\ \vdots & & & & & \\ F^{Q}_{1} & F^{Q}_{2\ldots\ldots} & P^{Q}_{1} & P^{Q}_{2\ldots\ldots} & R^{Q}_{1} & R^{Q}_{2\ldots\ldots} \end{matrix}\right\} \times \left\{\begin{matrix} K1 \\ K2 \\ \vdots \\ Kn \end{matrix}\right\} = \left\{\begin{matrix} C^{1} \\ C^{2} \\ \vdots \\ C^{Q} \end{matrix}\right\}$$

Figure 6.Data arranged in matrix form **(Eqn-1)**

The matrix operation above can be simplified as [F] x [K] = [C]. The aim is to obtain the K matrix, which consists of cost-coefficients. Matrices F and C consist of known data obtained from the samples. The superscript in the F matrix refers to the sample number and the subscript refers to the attribute number. In the C matrix the superscript is the sample number. Each row in the F matrix consists of the metrics of the functional, physical and reliability attributes of the sample model. Rows 1 through Q are the various samples of the model system. K matrix can be obtained by matrix manipulation using software such as MATLAB. A second order solution to the problem would give coefficient based on not just the cost drivers but the interaction between the cost drivers. Once the K matrix is obtained from equation above it can be directly applied to the target functions to estimate the cost of the target system.

Cost of Target = $K_1F^T{}_1 + K_2F^T{}_2 + \ldots K_iP^T{}_1 + K_jP^T{}_2 + \ldots K_gR^T{}_1 + K_mR^T{}_2 \ldots$ **Eqn-2**

F^T, P^T and R^T represent the functional, physical and reliability metrics of the Target system. Note that the equation-2 above is only one of the possible models. A variety of data fits can be obtained using the data from model samples. The flowchart in figure 7 explains how the framework works at systems level.

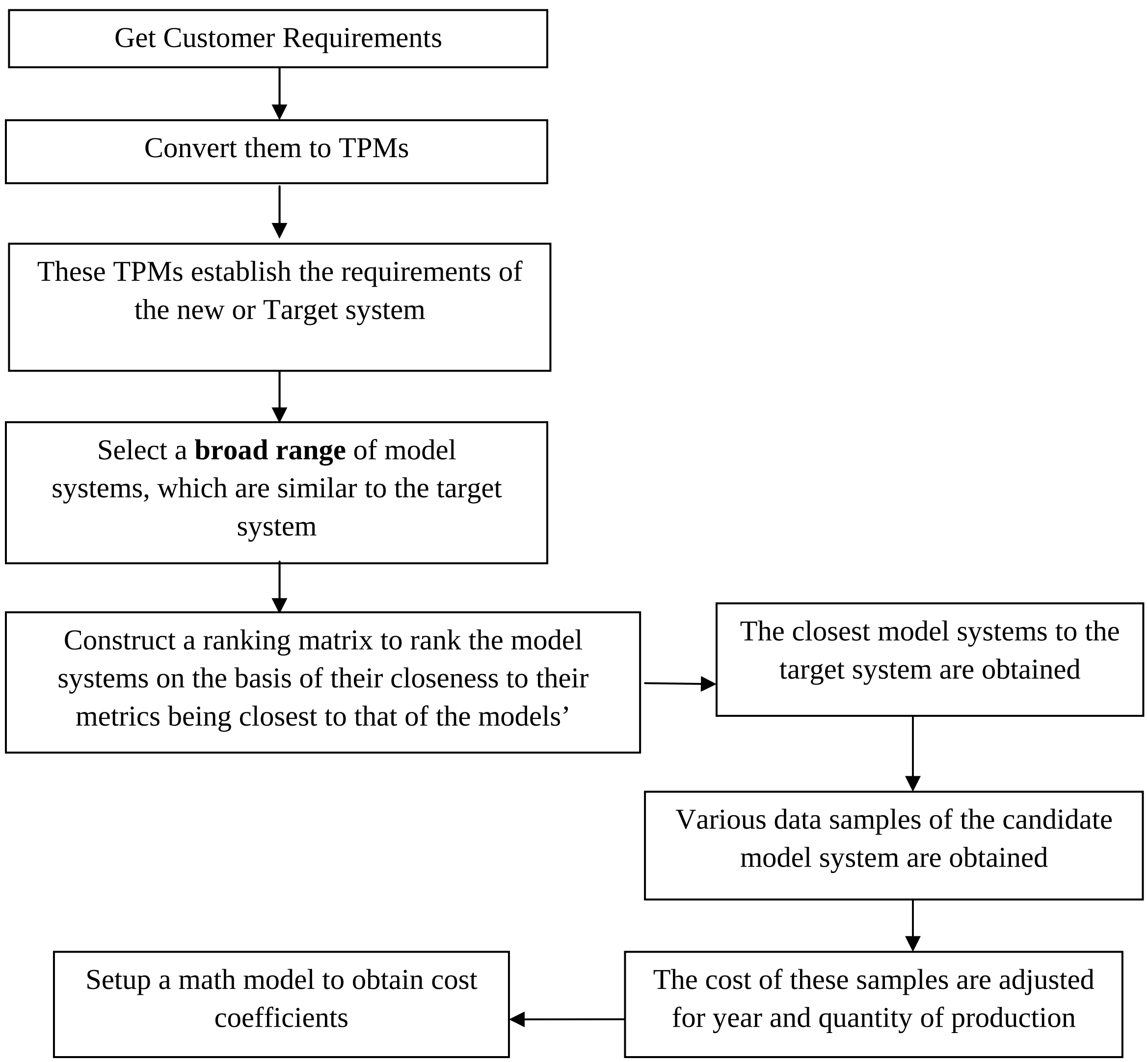

Figure 7. Flowchart of the Framework at Systems Level

5. METHODOLOGY AT SUB-SYSTEMS LEVEL

As discussed in the previous section the cost of the target system-functions that are not available in the prime model system can be calculated separately by following the same steps. If the missing functions are accomplished by a certain sub-system calculate the cost of the sub-system and add it to the cost of the target system. By the same token if the model system has a redundant function not required by the target system its cost can be calculated and subtracted from the cost of the target system. In either case the cost of this unit (sub-system/assembly/object) should be calculated. The procedure for calculating the cost of a sub-system is the same as that of a system shown in the flowchart in figure 8.

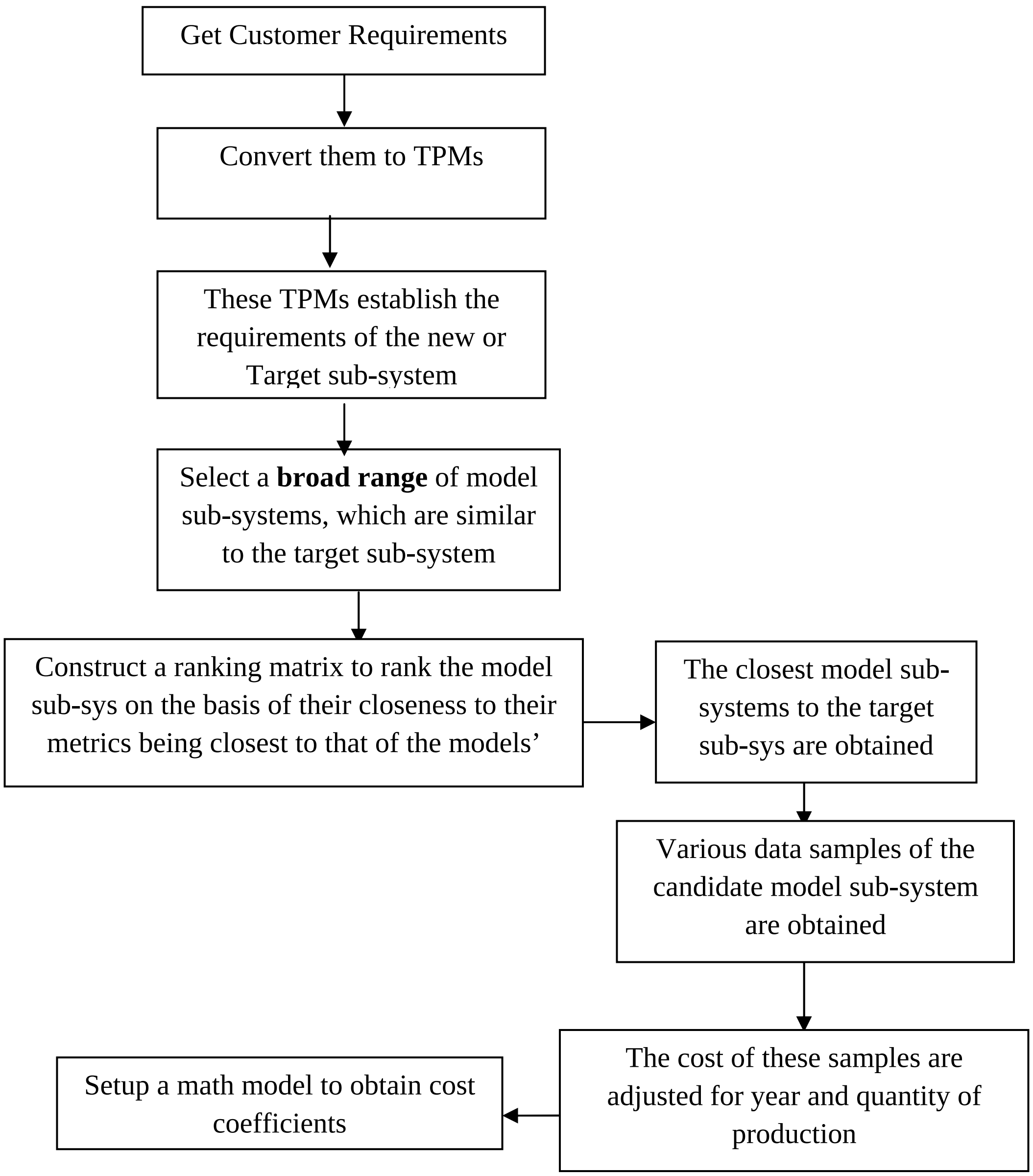

Figure 8. Flowchart of the Framework at Sub-Systems Level

As an example a cost model of a Rotary Air compressor is developed here. The data is collected from *MSC 2002/2003 Industrial Supply Co. catalogue*

	Rotary Air Compressor		
	CFM	HP	PRICE($)
1	27	7.5	5015
2	35	10	6545
3	53	15	6824
4	79	20	7912
5	97	25	8361
6	112	30	9256

Table 3Model Samples for Rotary Air Compressor

The first five records were used to come up with a cost model and it was used to predict the cost of the sixth item. The cost model setup was a simple MLR. The details are shown in table 4.

R Square	0.90
Adjusted R Square	0.80
	Coefficients
Intercept	4055.37
CFM	-35.07
HP	317.22

Table 4 Results from MLR

Cost = 4055.37 + (-35.0661)*(CFM) + 317.218*(HP)

When this model is applied to the sixth item in the table 3 (CFM of 112 and HP of 30) the cost comes to $9645, which is 5% off from the actual cost of $9256.

This is fairly accurate since the attributes and cost of an off the shelf product are well defined. The more information is available the more accurate the estimation. According to experts in the conceptual stage an estimate of 80% is good enough.

6. METHODOLOGY AT ASSEMBLY LEVEL

The next unit in the hierarchy is assembly. Cost of assemblies is a little more difficult to estimate then the cost of sub-systems since sub-systems exhibit functions or part of the functions of the system. But assemblies don't perform a function per se hence don't have cost drivers similar to that of sub-systems or systems. Also most often assemblies are one of a kind and will have to be custom made. This makes it difficult to obtain cost and cost-driver data from off the shelf items or industry. Typically at the conceptual stage not much information is available to calculate the cost in detail.

Assembly Cost Estimation: Assemblies can be classified into mainly three categories

1. Manual

2. Automatic
3. Robotic

Depending on the production quantity, quality and size one of these options is chosen. Boothroyd [4] has studied the assembly timings of vast variety of cases. We will show in figure 9 how the assembly process is incorporated into the framework of cost estimation.

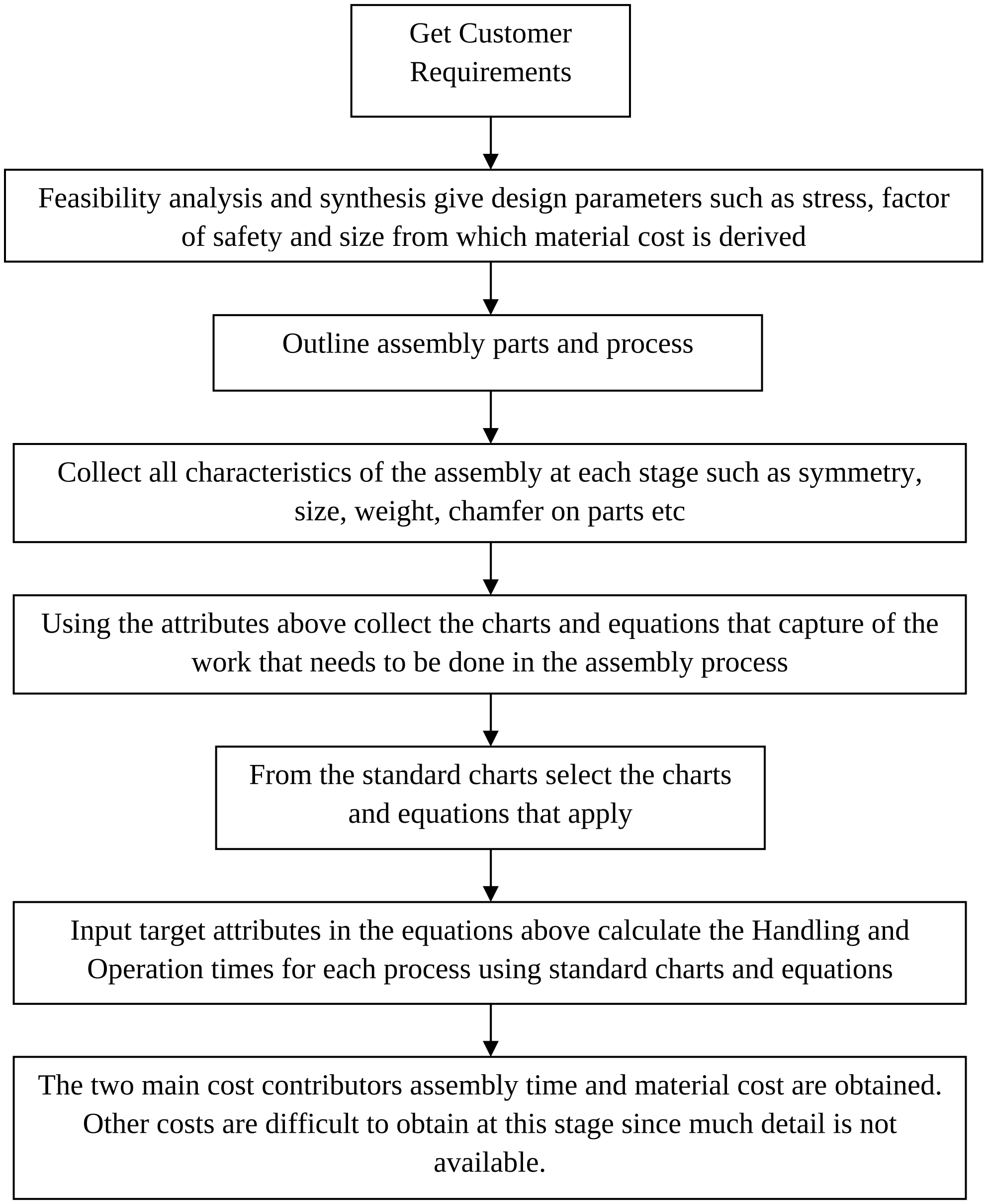

Figure 9. Flowchart of the Framework at Assembly Level

If the data collected in the charts and tables is not close to the situation then a custom chart/table can be created by experimentally finding assembly time for each assembly-process involved.

6.1 Manual

Lot of work has gone into calculating the cost of manual assembly. The scope of this paper does not permit to go into the details but the aim here is to include manual assembly into the fold of the framework. The equations and charts form the Model Assembly in this case. Some sample variables are shown in tables 5 and 6. Each of these attributes contribute to the time taken to assemble and hence the cost. The standard charts developed by Boothroyd [4] give the time penalties.

			Thickness													
	symmetry	No of parts	Cylindrical	Non-cyl	long cyl, thick = dia	tangling	Handling 1 or 2 hands	Grasping tool	no-secure	Secure by snap fit	Screw by power tool	no access	Restricted vision	Obstructed Access	Weight	Tweezers
Handling Time																

Table 5 Handling Time for various attributes of an assembly and its parts

	Threads	Slot-head	Philips-head	Allen	Philips w/tool	Slot-head w/tool
Operation Time						

	Clearance	boxend wrench	openend wrench	socket ratchetwrench	nuit driver
Run down time/rev					

Table 6 Operation Time for various attributes of an assembly and its parts

6.2 Automatic and Robotic Assembly

Charts similar to the one for manual assembly have been developed by G. Boothroyd [4]. These charts act as model in our case. In the context of this framework a model helps in building a math model of the cost through equations. The charts by G.Boothroyd are based on data collected for several assembly processes and with penalties for time lost due to several factors. The values obtained from these charts can directly be applied to the target.

7. METHODOLOGY AT OBJECT LEVEL

A part is the simplest unit in the hierarchy. As mentioned earlier a system consists of sub-systems, assemblies, and parts. But the smaller units are not always part of larger units. That is, not all components in the system are part of a higher sub-system. In such cases the cost of the parts would have to be calculated separately and added to the cost of the system. Cost of objects needs to be calculated since they form interface between the target system and the sub-system, which was not part of the model system. Objects are also constituent of assembly so their cost is important. The framework applies the same technique as shown above to calculate the cost of the part. The cost drivers in the case of a part cost estimate are the physical attributes of the features and processes used to machine. At this stage as part of the framework a tool is introduced called PRIMAs (Process Information Maps) [3]. PRIMAs helps select the process based on material and the number of parts required. Cost data pertaining to the process and feature attributes of model parts is collected. A math model gives the coefficients, which are then used to calculate the cost of the target part. As mentioned above PRIMAs gives a process but sometimes might be a very specific process for which data might not be available. In such cases another tool called the DCLASS (Decision CLASSIFICATION) [5] is used. DCLASS is the classification of processes into more and more specialized processes. Whenever detailed information about the process that needs to be employed is known then model parts on which those processes have been employed are used to draw a parametric model. When detailed information about the process is not known then DCLASS helps identify a generalized category of a fabrication process. Model parts with these generalized processes are then used to calculate cost model.

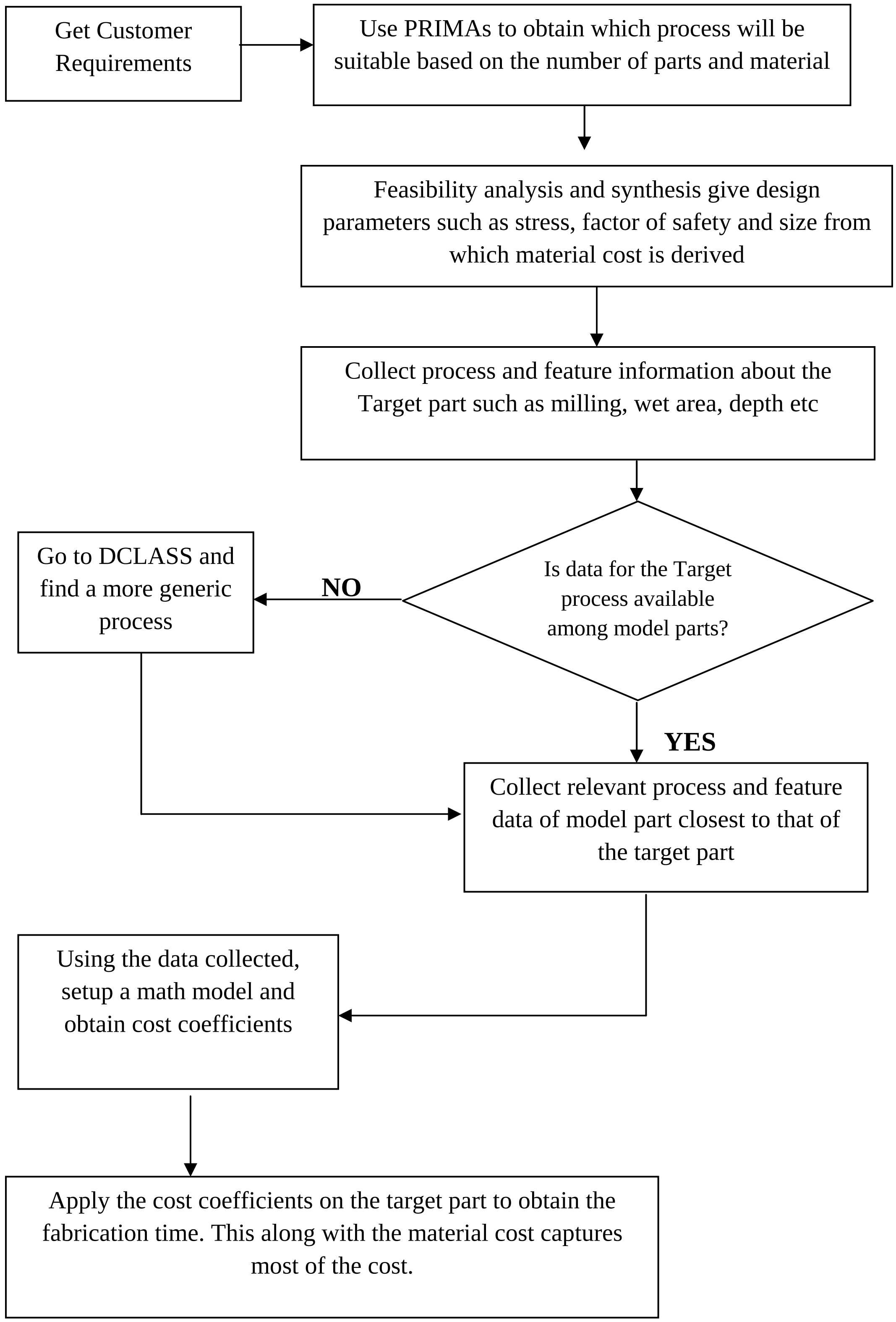

Figure 10. Flowchart of the Framework at Object Level

7.1 DCLASS

One of the many methods of classification of processes is the DCLASS taxonomy [5]. DCLASS was developed at Brigham Young university [5]. The purpose of classifying manufacturing processes is to club together similar processes into families. This helps in saving and retrieving data. This technique is very comprehensive in classifying fabrication processes. The general technique used is that each generic process is divided into specialized categories. As seen in figure 11 the sample classification from the DCLASS the fabrication processes are given a number [5]. This makes it easier to save the fabrication parameters such as the wet area, depth, machining speed etc; along with the fabrication process which is saved as a number in an electronic database.

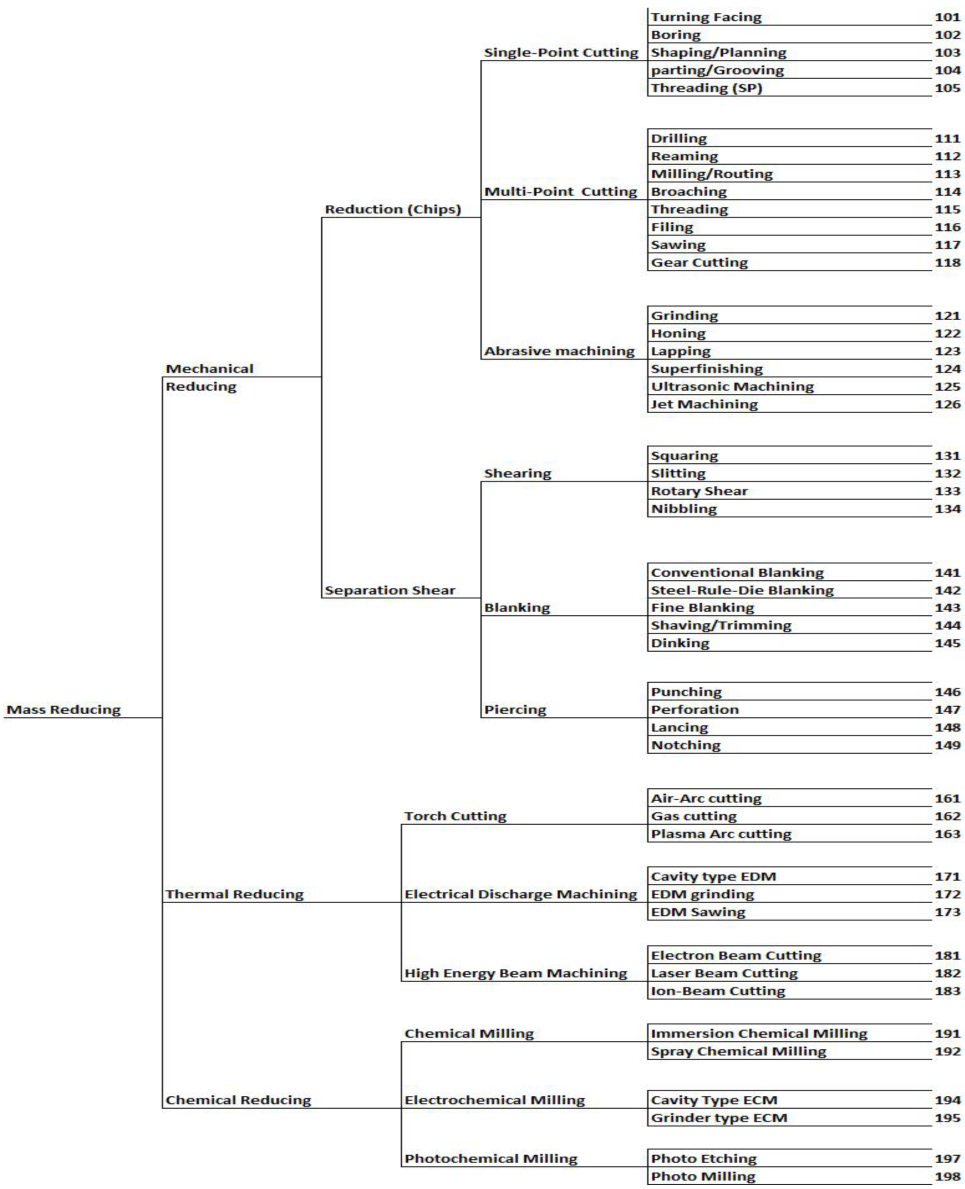

Figure 11. Breakdown of processes as per DCLASS

8. LIFE CYCLE COST

Lot of work has been done in the area of Life cycle cost estimation and model development. The aim here is to bring the life cycle cost estimation models into the realm of the current framework.

The life cycle cost equations that have been derived below [2] is the Model with respect to the framework. And the inputs specific to the system whose life cycle cost is to be estimated forms the target. An important point to note is that the framework in the case of systems and sub-systems obtains a model unit that matches closely to the target system. The samples of the model unit can be used to come up with a math model and set of equations. But in case of life cycle cost the equations themselves are a precedent Model.

<u>Life cycle cost Attributes</u>

AELCC = PC + OC + RC + SC

AELCC = Annual equivalent life cycle cost

PC = Annual equivalent population cost

OC = Annual Operating cost

RC = Annual repair facility cost

SC = Annual shortage penalty cost

AELCC

PC = C_iN

C_i = P(A|P,i,n) – B(A|F,i,n)

C_i = Annual equivalent cost

P = First acquisition cost of a system

F = Estimated salvage value of a system

B = Book value of a system at the end of year n

L = Estimated life of a system

N = No of systems in a population

N = Retirement age of a system, n> 1

i = Annual interest rate

Book value B is the present value of a system. It is calculated by subtracting the depreciation from the acquisition cost of the system.

B = P – n(P – F)/L

Annual Operating Cost OC

OC = (EC + LC + PMC + Misc)N

EC = Annual cost of energy

LC = Annual cost of labor

PMC = Annual cost of Preventive Maintenance

Misc = Cost of keeping the population of equipment in service, storage cost, insurance, premium etc

Annual Repair Cost RC
$RC = C_r M$
C_r = the annual fixed and variable repair cost per system
M = Number of systems repaired
The value of SC, annual shortage penalty cost is calculated if the repair channels are few and the population size is relatively small. If it is a production scenario this will result in a loss of production and hence penalty. In case of infinite repair channels and infinite population size (no queuing) Palm's theorem can be used to calculate the steady-state number in repair.

The author is working on making this aspect of the framework more robust and complex.

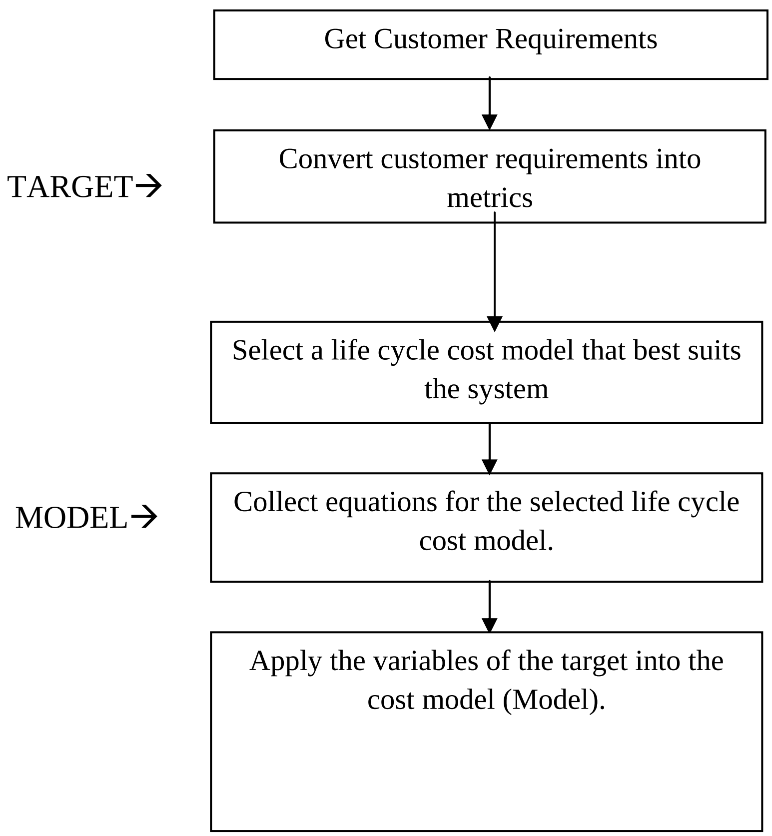

Figure 12. Flowchart of the Framework for Life Cycle Cost

9. RISK AND UNCERTAINTY

Statistical analysis of any data set that is stochastic in nature involves risk and uncertainty. Uncertainty is the amount of variation in the collected data. Both types of data, the cost of the model samples as well as the cost drivers can have uncertainty in them. The variation in the data can have any of the probability distributions such as normal, weibull etc. Risk on the other hand is the penalty that will be incurred as a result of uncertainty in the data. Uncertainty in the cost model arises because of cost driver data not taken properly or because of other varied reasons. Several techniques exist to evaluate uncertainty and risk such as Monte Carlo Method, fuzzy regression method, stochastic method etc. Work is being done to more effectively incorporate uncertainty and risk into the framework.

10. FUTURE WORK

Work is currently being done to make the framework more robust. An ontology is being developed at sub-system (product) level, which will work the same way as DCLASS works at object level. This helps put together a system efficiently on paper; locate a product with certain generic functionality and pull all necessary data to estimate the cost. The framework will be written in UML (Unified Markup Language). A database methodology will be developed that will link data related to objects, assembly and sub-systems. This will help in saving and retrieving data. The aim eventually is to develop software that can build and interpret a system and estimate the cost.

11. REFERENCES

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