COMPUTERIZED COST ESTIMATION FOR FORGING INDUSTRY

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
THE MIDDLE EAST TECHNICAL UNIVERSITY

BY

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IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE
IN
THE DEPARTMENT OF MECHANICAL ENGINEERING

SEPTEMBER 2003

Approval of the Graduate School of Natural and Applied Sciences

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ABSTRACT

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September 2003, 153 pages

In today's life, companies are faced with the problem of providing quality goods and services at competitive prices. Cost estimation is a very important process for a forging company, as each time a quote is sent to a customer, the company earns or loses money depending on the results of the particular estimate. However, determining pricing for customer quotes is a matter of time consuming, detailed number of tasks repeated each time. Cost estimation software might do those tedious calculations and assist the estimator step by step to reach to a cost estimate in relatively short time.

In this study, an interactive cost estimation software named "***Forge Cost Estimator***", which performs the early cost estimation for forgings, has been developed. The program is aimed to be used by the cost estimators in hot forging companies. The software has various databases, which include material, forging and machining equipment data. The cost items defined in the forging work breakdown structure can be estimated by using different modules of the software and summed up in an additive structure by using the bottom-up cost

estimation method. For calculating the forge volume quicker and easier, a new volume estimation system named "*Easy-Volume*", which is based on the volume fragmentation method, is proposed. The software can also guide the user in selecting the convenient forging production line. The software is written in MS Visual Basic 6.0. The developed program has been tested in a forging company and satisfactory cost estimations for several forgings have been achieved.

Keywords: Forging Cost, Forging Cost Estimation, Computerized Cost Estimation, Volume Estimation

ÖZ

DÖVME ENDÜSTRİSİ İÇİN BİLGİSAYARLI MALİYET TAHMİNİ

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Eylül 2003, 153 sayfa

Günümüzde firmalar ürün ve servis hizmetlerini, rekabet ortamına uygun fiyatlarla kaliteli bir biçimde sağlamak zorundadırlar. Bir dövme firması için maliyet tahmini, müşteriye verilen fiyat teklifindeki tahminin sonucuna göre kar veya zarar edilmesi nedeniyle çok önemlidir. Fakat, fiyat teklifleri için maliyet tahmininde bulunma işlemi, zaman gerektiren detaylı hesaplamalar içeren pek çok işlemin her seferinde tekrarlanmasını gerektirmektedir. Maliyet tahmin yazılımı, bahsedilen yorucu hesaplamaları yapabilir ve kullanıcıyı adım adım yönlendirerek nispeten kısa bir zamanda bir fiyat tahminine ulaşılmasını sağlayabilir.

Bu çalışmada dövme parçaları için fiyat tahmin işlemini yapan "**Forge Cost Estimator**" isimli interaktif bir maliyet tahmin yazılımı geliştirilmiştir. Yazılımın sıcak dövme endüstrisinde faliyet gösteren firmalar tarafından kullanılması amaçlanmıştır. Yazılım malzeme, dövme ve makine ekipmanları

verilerini içeren değişik veri tabanlarına sahiptir. Dövme iş ağacı yapısında tanımlanmış olan maliyet kalemleri, yazılımın farklı modülleri kullanılarak tahmin edilmekte ve birikimli bir yapıda aşağıdan yukarı fiyat tahmini yöntemi ile toplanarak sonuca ulaşılmaktadır. Dövme malzeme hacmini daha çabuk ve kolay bir şekilde hesaplayabilmek için, hacim parçalama methodunu kullanan "**Easy-Volume**" isimli yeni bir hacim hesaplama sistemi önerilmiştir. Program kullanıcıyı uygun dövme üretim hattının seçimi konusunda da yönlendirebilmektedir. Yazılım MS Microsoft Visual Basic 6.0 dilinde yazılmıştır. Geliştirilen yazılım bir dövme firmasında değişik parçalar için denenmiş ve tatmin edici sonuçlara ulaşılmıştır.

Anahtar Sözcükler: Dövme Maliyeti, Dövme Maliyet Tahmini, Bilgisayarlı Maliyet Tahmini, Hacim Tahmini

To My Family,

ACKNOWLEDGEMENTS

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SYMBOL

a_e : Depth of cut

A_f : Total projected area of the forging including the flash at the parting plane

a_p : Tool path interval

A_t : Total projected area of the forging excluding the flash at the parting plane

B : Width of the forging

B_t : Book value at the end of any year

C_{dht} : Die heat treatment cost

C_{fo} : Total factory overhead cost

C_{hf} : Heating cost per forging

C_{hkg} : Heating cost per kgf of forging material

C_{hlab} : Hourly direct labor cost

C_{kgdht} : Heat treatment cost per kgf of die material

C_{lab} : Labor cost

C_m : Hourly usage cost of the machine

C_o	: Overhead cost per forging
C_{op}	: Hourly operator cost
C_p	: Equipment usage cost per unit time
C_{tdm}	: Total die machining cost
D	: Maximum diameter of the forging excluding the flash
D_t	: Depreciation charge during any year
F	: Estimated salvage value
F_t	: Total load on the forging
K_p	: Forging equipment usage cost
L	: Length of the forging
H	: Height of the forging
h_m	: Mean height of the forging excluding the flash
n	: Estimated life of the asset
N_{lab}	: Quantity of direct workers
P	: First cost of the asset
P_r	: Production rate
Q	: Weight of the forging
Q_{die}	: Die weight
Q_e	: Weight of the enveloping shape
R_{dhl}	: Overhead rate on basis of direct labor hours
S	: Shape complexity of the forging
S_o	: Surface area of the material to remove
t	: Year
T_f	: Flash thickness

t_f	: Average forging time
t_{fdl}	: Budgeted direct labor hours
t_m	: machining time
t_{mill}	: Machining time in vertical milling
$t_{surmill}$	: Surface milling time
$t_{volmill}$	: Volume milling time
V_f	: Feed speed
V_o	: Volume of material to remove
Zs	: Surface rate
Zv	: Metal removal rate
W_f	: Flash width
WBS	: Work break down structure
ρ	: Density of the forging material

CHAPTER 1

COST ESTIMATION

1.1 Introduction

Product cost estimation is basically the process of determining the cost of a product. Cost estimation is very critical and important in all types of manufacturing processes. This study is concentrated on cost estimation of forgings manufactured by the hot forging process.

Forging is a commonly used production method, where materials are plastically deformed and shaped. Forging is a very detailed and complicated process, which requires a sequence of many operations. In Chapter 2, detailed information about the hot forging process is given. In this chapter, general cost estimation is explained.

Main industries like automotive and defense industry use forgings and generally buy forgings from the forging companies, instead of producing the forgings themselves. In daily life, customers send a fax or e-mail for the technical specifications, drawings and the properties like material type, quantity, delivery date, etc. of the forging product and want the "quote" from the forging companies.

In other words, customers basically ask from the forging companies:

"How much does it cost to produce the specified forging?"

The customers expect for the quotes a few days, from the forging companies. According to the given prices, the suitable offer is accepted and the job is given to the related forging company. In Figure 1.1, a schematic diagram of the job taking and production starting process is given [1].
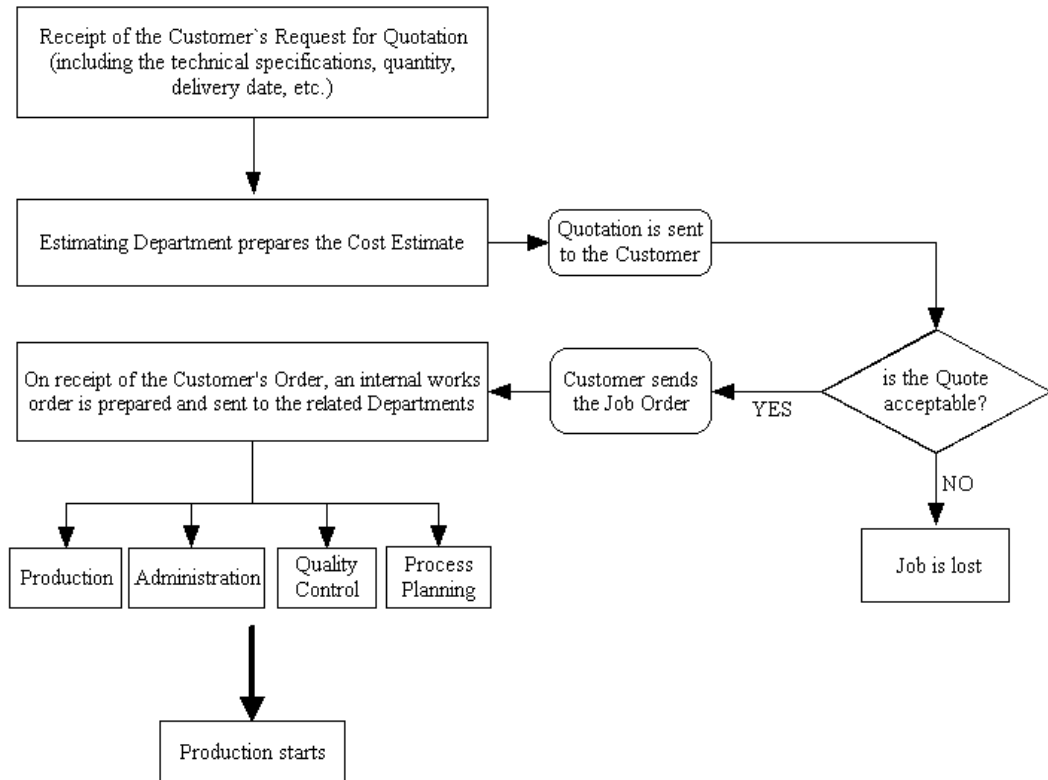
Figure 1.1 – Flow Diagram of Job Taking and Production Starting Process [1]

In forging industry, cost estimation is very essential. It is reported that a forging company receives at least 2 quote requests in each day [2]. Beyond the great effort that should be spent by the cost estimator, cost estimation requires speed, accuracy and consistency with the previous quotations. Over estimates will result in loss of the job to another company. Under estimates below the real value of the production costs will result in loss of money.

Cost estimation for the customer quotes is a matter of time consuming, detailed number of processes repeated each time. The items that form up forging costs like; material cost, labor cost, tooling cost, equipment cost, etc. should all be calculated each time.

1.2 Cost Estimation

Manufacturing a product involves the conversion of materials into finished goods by using labor and equipments. The cost of manufacturing a product is one of the most critical factors in a company's ability to meet competition. Today, cost is on the mind of every businessman. The objective is to minimize the cost, maximize the profit, and maintain the competitive edge. This can only be done, if the firm can properly estimate the cost of its products. Cost estimation is the evaluation and analysis of the cost of an operation, product or project generally derived by special methodologies [3].

Cost estimation is a critically important business function in all industries. Cost estimation is thought to be just writing the cost items in a list and then adding them, however manufacturing operations involve many cost elements that require analyzing [4]. An estimate is an attempt to predict the future and the thing, which characterizes an estimate, is the uncertainty [5]. The accuracy of the project and product cost estimations can often determine the ultimate success or failure of the company. Under competitive pressure, attempting to estimate without detailed cost information or wrong methodology can easily give two results; loss of the business or winning of the order but, having to perform the work at a loss [6]. Because, once a quote is sent to the customer, the company should obey the given production cost in the quote. Otherwise, the customer will think that this is not a serious firm and most probably, the customer will not give any job to this company anymore.

If the cost estimate is too high, other firms may give lower prices and the job will be lost to another firm in the competitive environment. If the cost estimate is too low, the job will be gained, but money will be lost. If a good quality cost estimate can be done, the job may be gained or may be lost assuming the other firms gave a lower price. If the job is lost, the managers will attempt to produce the products cheaper by corrections in the structure of the company and the manufacturing process. Therefore, true good quality cost estimates regarding winning or loosing the job will always be helpful to the company.

In many firms, the job of cost estimation is considered in the domain of the financial department. However, the cost estimation of products extends to every department of the company and especially into the engineering department and function. In today's business environment with the current automated cost estimation approaches, the engineers can also play an active and decisive role in cost estimation.

1.3 Cost Estimation Methods

There are four kinds of cost estimation methodologies used throughout the industry.

- Subjective estimation

- Estimation by analogy (comparative estimation, top-down estimation)

- Parametric estimation (statistical estimation)

- Bottom-up estimation (synthetic estimation, estimation by engineering methods, grass roots estimation)

In the subjective estimation method, the estimator obtains his price by relying completely upon his own memory and judgment without referring to the systematically collected data, which have been analyzed from previous work [7]. This is an unreliable and unsatisfactory method of cost estimation. Although it is an unrecommended method, it is widely used in the industry as a quick method to check the price or to give the customer a rough order magnitude of the price.

In the estimation by analogy method, the particular product is compared with the formal cost and technical data records of an old product. Allowances are made for any differences in material, weight, size, energy consumption, complexity and other factors to derive the product cost. The basis for the cost estimate is the similarity that exists between the known item and the proposed part. Estimation by analogy method is also named as top-down estimation method and comparative estimation method. The major disadvantage in estimation by analogy is the high degree of judgment required [8]. The analogous system

approach places heavy emphasis on the opinions of the cost estimators. Uncertainty in a cost estimate using analogy is due to the subjective evaluations made by the technical staff and the cost estimators during the determination of the cost impacts of the differences between the old and new products. Considerable experience and expertise are required to identify and deal with convenient analogies and to make adjustments for required differences.

There are two limitations in using the analogous approach. First is the requirement for a detailed technical definition of both the analogous product and the new product being estimated. Engineering judgment becomes the main basis of this approach. Without access to sound engineering support, this methodology is difficult to employ. Secondly, once the technical assessment has identified the analogous product, then the actual cost data on that product is required. Without actual cost data, the transition from the analogous product to the current product cannot be made [7].

Estimation by analogy takes less time; therefore, it is widely used in the industry as a check on the other methods and in the early cost estimation. For the forging industry, if there are analogous products available for comparative evaluation, analogy method can be used as a fast and early cost estimation method, especially for the cases when estimation time availability is too short.

The parametric or statistical estimation method involves collecting relevant historical data, usually at a convenient level of detail and relating it to the product to be estimated through the use of mathematical techniques [8]. The objective is to find a functional relationship between the changes in costs and the factors upon, which the cost depends. The important bases of the parametric estimation methodology are the *cost estimation relationships*. Each of the cost estimation relationships defines the cost as a function of the physical or operational parameters, like the speed, lot size, weight, complexity, horsepower etc. [5].

Statistical cost estimation method may utilize the statistical techniques ranging from simple graphical curve fitting to complex correlation analysis [9]. Generally, a detailed statistical study and the analysis of the related cost items are

required to derive a formula to express the total product cost. If a parametric formula can be established, it is fairly simple to use. However, parametric methods generally, capture the costs at a very high level, without going into too much detail [7].

In the bottom-up estimation method, the aim is to break down the job into its smallest tasks, based upon the best available information. The product cost is broken into small, manageable cost items. The cost estimator specifies each task, equipment and tool need, material requirement, labor cost etc. Then, the costs are assigned to each element at the lowest level of detail and then summed up to form the overall product cost [8]. Bottom-up estimation method is also named as synthetic estimation, engineering estimation and grass roots estimation.

Bottom-up estimation can be either broad or detailed, depending on the time available to the estimator and the required accuracy or the importance of the cost estimate. With full details and information, the bottom-up estimation method can give very accurate estimates [7].

The work elements and the cost items of a product or project and their interrelationships can be analyzed at successive levels of detail in the form of a *work breakdown structure* [5]. The work breakdown structure is a management technique for subdividing a total job into its component elements in a product-oriented hierarchy that identifies all elements of a product or project and their parent/child relationships. Forming of work breakdown structure is the first step in bottom-up method of cost estimation. The work break down structure is developed from the top (Level 1) to down in successive level of details. The job is divided into its major work elements (Level 2). The major work elements are then divided to develop Level 3, and so on. All work elements like product parts, product material cost, labor cost, maintenance cost, design cost etc. and their interrelationships must be shown in the work breakdown structure. The preparation of the work break down structure is essential in ensuring the inclusion of all work elements, eliminating the errors like duplications and overlaps between the work elements, showing the cost items level of details and giving an overall cost perspective about the product.

With this technique, it is started at the lowest level of definable work within the work breakdown structure, e.g. milling a die. The direct material costs are estimated. The labor hours required to complete the work are estimated from the engineering specifications and the labor costs are estimated usually using the company or general industry standards. The remaining elements of cost, such as tooling, quality control, and various overhead charges are estimated step by step.

The cost estimator may use variety of techniques in estimating the cost of each discrete work element. For example, the estimator may use an analogy to estimate one work element, a parametric cost estimation relationship to estimate a second work element. If the cost estimate for each work breakdown structure element represents the best guess of the cost for that particular element, then the sum of the cost estimate should be the best guess of the cost estimate for the whole system. One potential problem may be maintaining the documentation to support the estimate, since the cost estimate is the summation of many estimates.

The engineering or bottom-up method of cost estimation is the most detailed of all the techniques and the most costly to implement, however its benefits are dramatic [10]. The disadvantages and limiting factors for this approach are the time consuming nature of the tasking and the need for very detailed actual cost data. Although this method can be complex and time consuming, it is the method of choice when good accuracy is required.

1.4 Detail and Accuracy Level in Cost Estimation

There are three kinds of cost estimates considering the level of detail and accuracy; order of magnitude estimates, semi-detailed estimates and detailed estimates [5].

Order of magnitude estimates provide accuracy in the range of ±30 to 50%. In this range of accuracy, the estimator generally makes specific detailed cost estimations considering the cost items only at level 1 or level 2 in the work breakdown structure.

Semi detailed estimates provide accuracy in the range of ±15 %. In this range of accuracy, the estimator generally makes specific detailed cost estimations considering the cost items only at level 2 or level 3 in the work breakdown structure.

Detailed estimates provide accuracy in the range of ±5 %. In this range of accuracy, the estimator generally makes specific detailed cost estimations considering the cost items at level 3 and successive levels in the work breakdown structure.

Accuracy range variations result from the differences in the details of cost breakdowns and the amount of the time and effort spent on the estimate. For better cost estimation results, a more detailed work breakdown structure should be prepared considering all the cost items. The accuracy of cost estimate depends on the amount and quality of the information, the available time and the qualification of the estimator, as the personal opinion is inescapable in cost estimation [3].
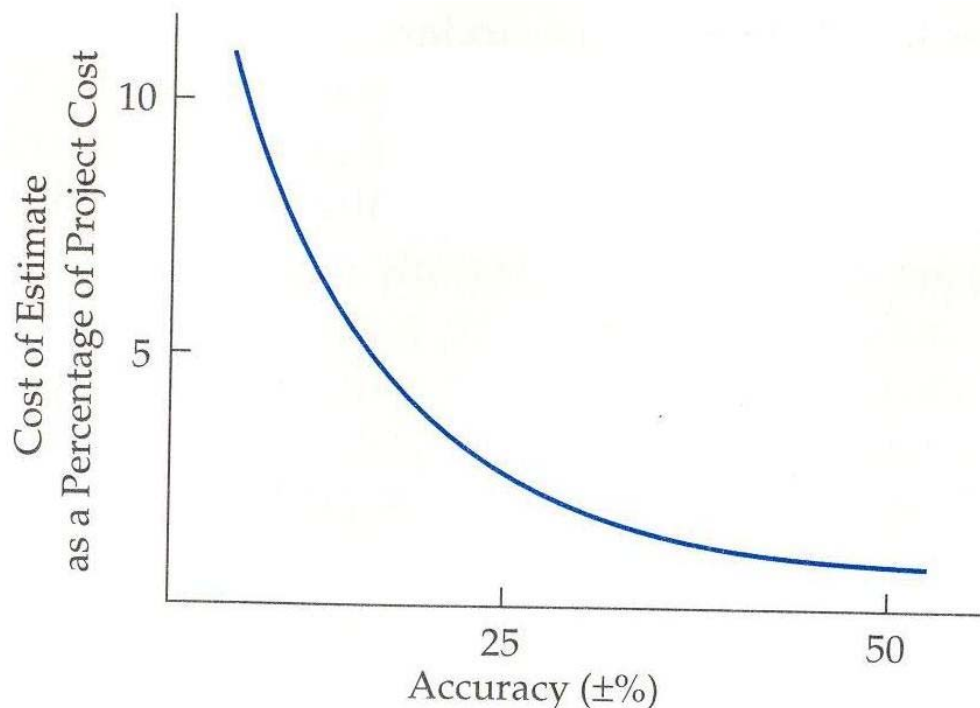
Figure 1.2 - Accuracy and Cost of Estimation Relationship [5]

As estimates become more detailed, the cost of estimation increases dramatically [5]. The more accurate the estimate, the more time required for its preparation. This is shown in Figure 1.2. As finer levels of detail are investigated, cost and time to prepare the estimates increase to an unacceptable level. Therefore, the cost estimates should be prepared considering the required accuracy and importance of the study.

1.5 Computer Aided Cost Estimation

Hand recording and computing methods are slow and costly, when large and complex operations should be closely controlled through the use of timely and accurate cost information [11].

During the recent years, the value of computer aided cost estimation has grown as a manufacturing tool. The computers can be employed to produce the cost estimates using the same techniques that have been developed for manual cost estimation. By using computers, better quality estimates or the same quality can be produced quicker and cheaper.

The value of computer-aided cost estimation in the forging industry is mainly two-fold. First, the estimation process is accelerated for savings in time. Second, existing skills and experience can be rationalized and programmed for interactive use and also for easing the problem of training new estimators. By using computers, the individual experience can be transformed into the company experience.

The application of computers in the cost estimation process offers many advantages to cost estimators. Basic advantages are the speed and the accuracy. Cost estimation often involves complex mathematical calculations and requires advanced mathematical techniques. The computer is fast and may relieve the estimator of much of the job of making numerous calculations, which involve chances for making errors. However, although the computer may be able to complete a job in a matter of seconds, the time required for developing and entering the inputs may take a time of several minutes or hours.

The computer provides a useful documentation aid. The data inputs, calculations and results may be saved on data storage devices (diskette, disc, CD, etc.) as a soft copy, which facilitate revision and reprocessing in future. Computers are also used to produce all of the necessary documentation with the help of word processing and spread sheet software, leaving the estimators more time to study and analyze the cost estimation.

Observing the effect of changes in the inputs on the output becomes more practical by using a computer aided estimation program, as examining a range of cases and variations in the inputs is easier compared with the manual cost estimation. For example, the forging line that will be used can be changed or the die material can be changed and the results can be obtained just by using several buttons of the software. The cost estimation software may repeat all calculations in a short time.

It should be known that the computer is a tool to assist in the performing of estimates and not a substitute for the estimator. Basically, the computer is a tool to complement the estimator. The computer program can be too automated for the benefit of the user, but it can never be a substitute for the ability of the estimator to develop reasonable and realistic inputs based on the judgment and experience [32]. Although, computers cannot be used for the entire estimation process, they can relieve estimators of much of the hard work associated with routine, repetitive, and time consuming calculations.

1.6 Previous Studies

Forging cost estimation requires theoretical and practical knowledge of the forging process. However, forging cost estimation is not only related with forging process or engineering; it is also related with economics and cost accounting.

A railroad civil engineer Wellington in the latter part of the nineteenth century addressed the role of economic analysis in engineering. This primary work was followed by the others to define techniques that depend on financial mathematics. In 1930, Grant published "Principles of engineering economics"

which was a milestone in the development of the engineering economy [5]. After this date studies continued increasingly.

The importance of the engineering cost specialty is an accepted fact and increasing studies and activities in the industry is observable now. The increasing global competition forces all types of the industries to lower the profits and produce low cost and high quality products. Studies on engineering economy, cost accounting and cost estimating, which are related disciplines continued due to the importance of the subject [3 - 11].

Many scientists have studied cost estimation, for different categories of products. Bruckner studied on cost information for gear drives. Ou -Yang and Lin developed an integrated framework for feature based manufacturing cost estimation at an early design stage [13].

In the studies of Nagarajan and Santos, a computer aided cost estimation system for cost estimation of electronic cards produced with ball grid array and direct chip attach technologies is developed [12].

A few number of cost model systems have been developed for estimation of the manufacturing cost of injection molding components. Shining studied on designing a cost based system for molded parts [13]. Chen and Liu studied on cost effective design of injection molding [14]. Güler and Gökler studied on evaluating the early cost for plastic injection molds [15]. In this study, final cost was separated into additive cost items, which are assigned to individual mold functional components. After inputting molding properties like geometrical dimensions, surface quality etc. the program outputs the total cost for the molds.

Mohammed and Celik studied computer-aided cost estimation of the building construction [16].

Many scientists have studied machining costs. Shaw [17] and Boothroyd [18] studied on machining and metal cutting techniques and offer methods for time estimation in machining. Bouaziz studied on evaluating machining costs in plastic blowing molds [19]. This study, which is based on classical machining formulas, is also convenient to apply on forging die machining cost estimation.

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It is reported that Berlioz studied on defining a fast and reliable method of cost estimation for hot forging [19]. This study is based on an empirical formula. However, empirical formulas may only be useful for particular parts and well defined work. For the forging process, production methods and efficiency of plants may deviate too much from plant to plant and an empirical method may not seem to be a convenient method for cost estimation in various plants. Bly studied economics of induction heating for forging process and stated that the induction heating can be much cheaper according to oil-fired furnaces and high production rates can be obtained [20]. Bariani studied tool cost estimation for cold forging process [21].

If cost estimation programs in the market are analyzed, it can be seen that there are various estimation programs from very complex to simple for various kinds of sectors like machining and construction. Examples are; Costimator, DeccaPro, ProEst, etc. However, there is a lack of forging cost estimation program in the market. This can be due to the complexity of the process, which may deviate from plant to plant. For forging process, there are no standardized cost estimation rules. Basics of forging cost estimation process are similar with other cost estimates. However, practically each company needs its own cost estimation program, as the cost estimation methodology and the expectations of the customers from the program may deviate.

The above literature review shows that different cost models have been developed for various kinds of applications. Different researches studied on the economics of the forging process in different levels, while they are studying on different aspects of the forging process [20 - 43]. But little effort was made in the computer aided forging cost estimation. In the following chapters, related literature information and references will be given within the related sections.

1.7 Scope of the Thesis

The cost estimation is very important in all types of the industries and especially for the forging industry. The cost estimation should be as quick as possible. Each time, a quote is sent to a customer, the producer bets his business

on the accuracy of the costs in the estimate. Therefore, speed and accuracy are the main factors on the cost estimation. However, determining pricing for customer quotes is a matter of time consuming, detailed number of tasks repeated each time. The items that form up forging costs like; material, tooling, labor, equipment, overhead, heating, cleaning, inspection, heat treatment, coating, painting, transportation etc. costs should all be calculated each time. Computers might do those tedious calculations and assist the estimator step by step to reach to a product cost in relatively short time. Computer aided cost estimation can be a helpful tool with visual interactive menus and computation ability. More reliable and faster estimates can be done with computer-aided estimation.

Nowadays, computerized cost estimation programs are being available in the market for different processes, as mentioned before. However, there is a lack of forging cost estimation program in the industry. Computers can also be used in the area of the forging cost estimation.

Main scope of the thesis is developing a cost estimation software, which performs the early cost estimation process for forgings. The program is aimed to be used by the cost estimators in hot forging companies. By means of this software, the cost estimation process is computerized and automated to provide fast and to some extent accurate results.

In Chapter 1, general information on cost estimation has been given. In Chapter 2, information about the forging process and the cost related items are given.

In Chapter 3, the forge volume estimation process and the volume estimation software module "*Easy-Volume*", which is a new proposed system for calculating the forge volume quicker and easier, are presented.

In Chapter 4, forging cost estimation methodology is given. The forging breakdown structure has been considered to define the cost items of the forging process. The cost items are estimated and summed up in an additive structure by means of a bottom-up cost estimation method.

In Chapter 5, overall structure of the forging cost estimation software is defined with the aid of the flow diagrams.

In Chapter 6, the forging cost estimation software is presented and a sample estimation process is given.

In Chapter 7, conclusions and final remarks are given.

CHAPTER 2

COST ITEMS IN HOT FORGING

2.1 Hot Forging

Forging is defined as the plastic deformation of metals by applying compressive forces by manual or power hammers, presses, or special forging machines [22]. Forging process, generally includes sequential deformation steps, which gradually bring the workpiece to the desired final shape. The forging operation can be done cold, warm or hot. In hot forging, the stock material is heated above its recrystallization temperature (about 1000° C - 1300° C) by using special furnaces. At these temperatures, obtaining a bulk deformation requires less compression force. The products of forging process are called forgings.

The degree of the structural reliability and high strength to weight ratio achieved in the forging process, make the forgings the best choice for high performance, high strength, high reliability and long term usage applications, where tension, stress, load, and human safety are critical considerations. Forgings are widely used in the automotive industry, defense industry, marine industry and aerospace industry, agricultural machinery, off-highway and railroad equipment, valves, fittings, petrochemical applications, industrial hardware and hand tools. Parts such as connecting rods, piston rods, crankshaft in a car, landing gear supports, wheels, propeller blades in an aircraft are produced by forging process.

Forging is an expensive process. Cost of the dies and the machinery used are high; so forging should be considered in where large quantities of products are intended to be produced with mass production. Forging can be classified into two as closed die forging and open die forging. Closed die forging is the shaping of

the hot metal between the cavities of two dies. In closed die forging, preform shapes are often formed by preforming dies to ensure proper metal distribution and flow.

Closed die forging is highly applicable for large production series of parts where there is high demand on strength and toughness. The main disadvantage compared to open die forging is the tool cost. Merits in closed die forging are: optimal microstructure, complicated forms, low amount of machining and efficient use of material.
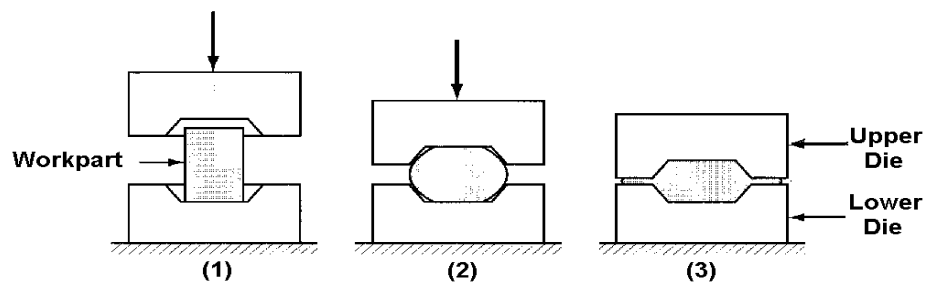
Figure 2.1 - Closed Die Forging [1]

Open die forging involves the shaping of heated metal parts between a top die, attached to a ram and a bottom die attached to a hammer anvil or press bed. Metal parts are gradually shaped into the desired configuration through the skillful hammering or pressing of the workpiece. While closed die forging confines the metal in dies, in open die forging metal is never completely confined or restrained in the dies. Most of the open die forgings are produced on flat dies. Round swaging dies, V-dies, mandrels and pins may also be used [23].

In open die forging, geometry of the forging is not fully controlled and is especially used for forgings that are large to be produced in closed dies, for low volume production, test sample prototypes and for raw forming of the part to be machined. Bars, step-down shafts, ship propellers are some examples to open die forging. The main disadvantages are high machining costs required after forging.

Figure 2.2 - Open Die Forging [22]

Forging can be classified according to the type of the equipment that is used as drop forging, press forging, upset forging, roll forging etc. This study is concentrated on drop and press forging.

In drop forging (hammer forging) technique, the upper die block on the ram drops on the lower die assembled on anvil to shape the metal billet. There are gravity drop hammer types and power drop hammer types. In gravity drop hammers, the ram accelerates by the gravity and builds up the blow energy, whereas in power dr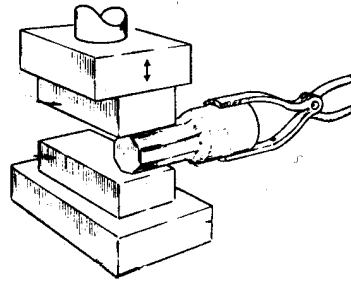op hammers, the ram is accelerated by the steam or air in addition to gravity. The heated metal billet is positioned in the lower cavity and struck with one or more blows by the upper die. The hammers initial costs and operation costs are cheaper compared to the presses [24]. In Figure 2.3, the general structure of a sample power drop hammer is shown.

In press forging technique, the slow squeezing action penetrates through the metal and produces a more uniform metal flow. Due to the controllable slow motion of the ram, very good tolerances can be obtained. Depending on the source of the power, forging press is classified as hydraulic or mechanical. Mechanical presses use flywheel and clutch to provide the motion, whereas hydraulic presses use hydraulic power to provide the motion. Hydraulic presses are slower and more costly to operate, but they can provide greater capacity to forge huge parts. Capital cost of a forging press is higher than that of an equivalent capacity hammer, but production rates are much higher and precision

is generally better [25]. Mechanical presses are the most widely used equipment in the industry for closed die forging operations [26].
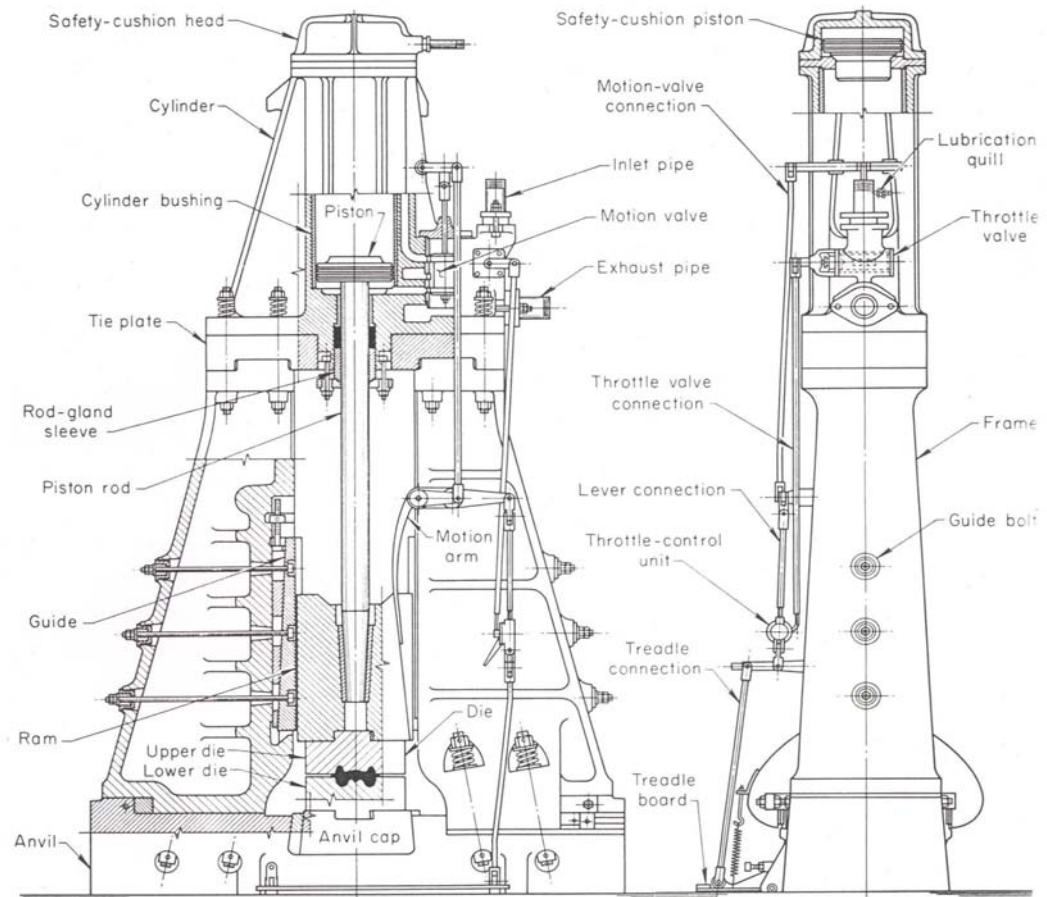

Figure 2.3 - Power Drop Hammer [34]

In this section general information on hot forging process is given. Detailed information on hot forging process may be found in several literature [23, 24, 26, 29, 30, 31, 33].

2.2 Design of the Forging Part and the Forging Process

Three main phases must be completed before a forging is put into production [27].

a) The appropriate forging should be designed from the required machined part.

b) Forging process for the specified forging should be designed. The method and sequence of operations should be decided upon, including the estimates of the amount of material required.

c) The appropriate dies for preforming and finishing operations should be designed.

The following sequence is a common basic design process for forgings [28].

- Machining allowance must be added to surfaces that will be machined.

- Parting plane is located.

- Draft must be given to surfaces, which are perpendicular to the parting plane.

- Fillets and corner radii should be used to blend the sharp corners.

In forging industry, it is common that the design of the forgings are carried out by the customer. In technical drawings sent by the customer; machining allowances, drafts and edge radii are included and the forging company is asked to produce an already designed forging [2, 27]. Thus, generally, only the last two phases are carried out by the forging company.

1) Calculation of the forging volume and the weight is the first step in forging process design. To determine the raw material dimensions, the amount of metal required to assure complete die filling should be estimated; considering flash, scale, tong hold and die wear. Forging billet cross section and length will be determined according to the forging volume.

2) The required forging load is calculated. The forging method and equipments should be selected considering the forging load, forging material and forging dimensions.

3) Number of stages and the shape of the part at each stage are determined.

4) Forging dies are designed considering;

- parting plane location, draft angle, fillet and edge radii, the grain flow direction, machining allowances and webs for large holes.

- number of intermediate steps and the shape of each die

- the final forging shape

5) Forging dies are manufactured and heat treated. It can be noted that, the design of the dies requires expertise and past experience.

6) The dies and the forging equipment are set up for the forging process.

7) The forging stocks, which are round or square cross section bars, should be cut from proper length to form the forging billets to include the required amount of forging material.

8) The forging billet is heated in the furnace and positioned on initial preforming die. Then preforming impressions are done step by step and finally in the final forging die, the forging is forged to obtain the desired shape.

9) Excess metal squeezed around the periphery of the cavity named flash, is trimmed of by means of a trimming die in a trimming press. For holes, punching impression is done by a punching die in a press.

10) Secondary operations like sand blasting, acid bathing, heat treatment, coating and painting may be applied.

11) The quality control operations are carried on during the whole process.

12) Finally, the forgings are packaged and sent to the customer.

The forging cost estimation process should include all activities described in these steps. In the following sections, further details of the forging process parameters, which are related with the forging cost estimation, will be discussed.

2.3 Material Losses

The "scale" or iron oxide is caused due to the contact of the heated steel with air. It is preferred to minimize the scale formation and remove the scale before the billet is put into the die. The scale falls of during forging process and remaining scale should be cleaned by special operations after the forging process. The scale formation results in material loss, therefore a scale allowance have to be applied to the calculations of the forging billet volume.

The amount of scale depends upon the material type, type of the furnace, proportion of the oxygen in the furnace, forging temperature to which the material is heated and the heating time [29]. Many of these conditions depend on human factor in majority of the plants. Therefore, scaling material losses cannot be precisely calculated, but can only be estimated as an approximate percentage of forging weight. Sharman assumes scaling weight to be in between 5 to 10 percent of the net forging weight [30]. Sabroff found that scale weight tends to decrease on a percentage basis with increasing weight [31]. Referring to this study, the scale loss can be assumed to be 5 percent of the net weight for parts below 4.5 kgf, 4 percent of the net weight for parts between 4.5 - 11.5 kgf and 3 percent of the net weight for parts above 11.5 kgf.

Bruchanow and Rebelski concluded that the scale allowance depends on the type of the furnace in which the metal is heated and recommended the values given in Table 2.1 [32].

Table 2.1 - Scale Allowances [32]

TYPE of the FURNACE	SCALE ALLOWANCE
OIL BOX	4%
GAS BOX	3%
GAS CONTINIOUS	2.5%
ELECTRIC	1.5%
INDUCTION	1%

Excess material surrounding the forged part at the parting plane is called "flash". Flash extruded from the finisher impression during forging acts as a cushion for impact blows and as a pressure relief valve for the work metal [22]. Flash restricts the outward flow of the metal, so that thin ribs and bosses can be filled. Efforts are made to eliminate the flash, but then filling the die completely will require a close control of the stock and higher forging loads are required [24]. The flash is trimmed off from the forging after the final impression with a trimming die.
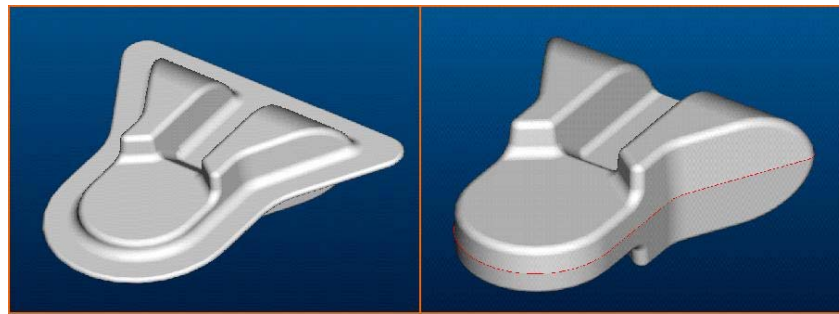

Figure 2.4 - A Forging with Flash and After Flash is Trimmed off

Many scientific studies have been done to analyze and explain the flash formation. For axi-symmetric and uniform in section forgings, where parting lines are planar, the weight of the flash is less than 5 percent of the forging weight [33]. Depending on the size of the forging, flash losses may generally be about 5 to 15 percent. But losses up to 30 percent are reported for high and narrow forgings [31].

In general, the flash thickness increases with the weight of the forging [30]. The volume, the shape complexity and the height to weight ratio of the forging, and the type of work metal have effects on the flash thickness [26]. The flash thickness varies from 0.5 mm up to 9.5 mm for forgings weighing up to 90 kgf

[34]. It is reported that the flash thickness increases with the forging weight, while the ratio of the flash width to flash thickness decreases to a limiting value [23].

Neuberg and Moeckel classified 1500 forgings from different companies in to shape groups as suggested by Spies to establish a relationship between forging shape, weight and flash dimensions [35]. Following scientific studies showed that the influence of the shape is not as significant as that of the forging weight on the flash dimensions [24].

In literature, several formulas and tabulated results are available for determining the flash thickness and width.

Bruchanow and Rebelskii suggested determining the flash thickness, 'T_f' in mm as a function of the projected area of the forging at the parting plane, 'A_t' in mm^2 by using the following expression [32]:

$$T_f = 0.015 \sqrt{A_t} \tag{2.1}$$

Voigtlander has also derived a formula for determining the flash land ratio, W_f / T_f which is revised by Thomas for axi-symmetric forgings as follows [32]:

$$T_f = 0.016\, D \tag{2.2}$$

$$W_f / T_f = 63 / \sqrt{D} \tag{2.3}$$

where, 'D' is the maximum diameter of the forging in mm excluding the flash, 'T_f' is the flash thickness in mm and 'W_f' is the flash width in mm.

Wolf suggested empirical equations 2.4 and 2.5 applicable for most of the forgings [24].

$$T_f = 1.13 + 0.89\sqrt{Q} - 0.017Q \tag{2.4}$$

$$W_f = T_f * [3 + 1.25e^{-1.09Q}] \tag{2.5}$$

where, 'Q' is the weight of the forging in kgf.

23

"National Association of Drop Forgings (NADF)" recommended a method for estimating the flash weight. In this recommendation, the flash weight is calculated by multiplying the periphery of the forging along the parting plane by the flash thickness, flash width and material density [36]. Approximate flash thickness and width per unit length of the periphery of the forging, considering the forge weight are given in Table 2.2.

Table 2.2 - Approximate Flash Thickness and Width per unit Length [36]

Forge Weight: (kgf)	Flash Thickness: (mm)	Flash Width: (mm)
Up to 0.5	3.2	19.1
0.5 – 2.25	3.2	25.4
2.25 – 4.25	4.0	31.8
4.25 – 6.75	4.8	34.9
6.75 – 11.33	5.6	38.1
11.33 – 22.67	6.4	44.5
22.67 – 45.33	8.0	50.8
45.33 – 90	9.5	63.5

A "tong hold" provides a holding piece for the transfer and manipulating of the material during forging, and for handling during clipping. Many of the forgings do not require extra tong hold projections, as their shapes are convenient to be hold by tongs [2]. Projections used for holding or ejecting the forgings, consume material and must be considered in calculating the forging billet weight [31]. For heavy forgings, the weight of the tong hold loss increases as strength requirements increases [30].

Forging billets are cut from the standard bar stocks with a standard length, by using abrasive wheels, sawing equipment or cropping blades. If the stock is

sawn, some amount of material is removed by the saw blade, which is called "saw cut waste". In cropping by blades, there is no saw cut waste, however blades have dimensional cutting capacity limitations.

During cutting of the bar stock some pieces, that are shorter than the required billet length are left at the end of the stock. Those parts cannot be used for the particular forging process, as required amount of material is not included. The waste material on short bar end pieces left from stock is named as "bar end loss". Sabroff suggested that the bar end wastage is about 3 percent to 6 percent of the net forging weight [31].

Forging dies wear out after each impression and if the tolerances are not tight, dies are held in service as long as possible without remachining. For the cases where the die wear is significant and the tolerances are not tight, the worn out forging dies hold more material than they should normally hold. If the waste material due to die wear will be considered, an addition of 4 percent of the net weight is recommended [31].

2.4 Forging Equipment Selection

Forging equipment is selected considering: required forging force, forging shape complexity, forging dimensions, forging weight, forging material type and quantity [2, 24, 36].

a) Forging Force and Forging Shape Complexity

The prediction of forging load is an extremely difficult task as most of the forging operations are of non-steady state type in terms of metal flow, stresses and temperatures. The metal flow, friction at the die and forging material interface, the heat transfer between deforming material and the dies vary continuously during the forging operation [36].

There are three methods to obtain forging loads; estimation by experience, estimation by analytical methods and estimation by empirical methods.

In estimation by experience method, estimates are based on previous forging of similar parts. Estimation by experience method is widely used in the industry. However, this is not a scientific and reliable method as it depends on human opinion, which might vary from time to time. Estimation by experience can be used as a check on other methods.

In analytical methods, load and stresses are calculated for separated smaller components of the forging to sum up later on [24]. Analytical methods like slab method and elemental upper bound method, which are based on the fundamental phenomena of metal deformation and flow, generally gives the best results. Therefore, analytical techniques should be used for predicting forging pressure and load [23]. However, analytical methods require a large amount of engineering time. Although some package software are available in the market, running time on computers may take several hours to days. It is not practical to apply analytical methods in an initial cost estimation program.

Empirical methods are developed by experience and statistical data. Empirical methods, which use some formulas or curves that are found from several experimental data, are usually sufficiently accurate for estimating average forging pressures and maximum forging loads under practical shop conditions [24].

To calculate the forging load, the projected area of the forging at the parting plane is multiplied by an average forging pressure. The forging pressure depends on the material and geometry of the forging [23].

Drop Forging Research Association (DFRA) suggested a general form of equation based on analytical slab method [36].

$$F = \sigma_y * A_t \tag{2.6}$$

where, σ_y is a function of $W_f / (T_f * h_m)$

$$F_t = a * (h_m)^p * (W_f / T_f)^q * (A_t)^r \tag{2.7}$$

where, F_t : total load on the forging in tonf

h_m : mean height of the forging excluding the flash in mm

W_f : flash width in mm

T_f : flash tickness in mm

A_f : total projected area of the forging including the flash in mm^2

a, p, q, r : constants

DFRA equations obtained by regression analysis are presented in the following form:

For simple forgings;

$$F_t = 0.0354 * (W_f / (T_f * h_m))^{0.025} * A_f \qquad (2.8)$$

For complex forgings;

$$F_t = 0.0538 * (W_f / (T_f * h_m))^{0.009} * A_f \qquad (2.9)$$

Mean height of the forging excluding the flash 'h_m' can be calculated by dividing the forging weight, 'Q' to the density, 'ρ' and the projected area of the forging excluding the flash, 'A_f' [24].

$$h_m = Q / A_t * \rho \qquad (2.10)$$

Metal flow in forging is greatly influenced by part or die geometry. Several operations are needed to achieve gradual metal flow from an initially simple cylinder or square prism shape billet to a more complex shape of the final forging.

The number of required performing operations and required forging force are determined essentially by the geometrical complexity of the forging [23]. In planning the forging operations, estimating the required forging force and selecting the convenient equipment; defining an objective and reproducible quantity representing the forgings shape complexity is useful.

The shape complexity of a forging can be represented by S and found by the formulation:

$$S = Q / Q_e \qquad\qquad (2.11)$$

where, Q : weight of the forging

Q_e : weight of the enveloping shape

If the value of the shape complexity S decreases than the required material deformation increases and the required forging load increases. If the S value is greater than 0.63, the forging can be defined as simple forging and if the S value is smaller or equal to 0.63, the forging can be defined as complex forging [25]. Examples for the enveloping shapes for forgings are given in Figure 2.5.
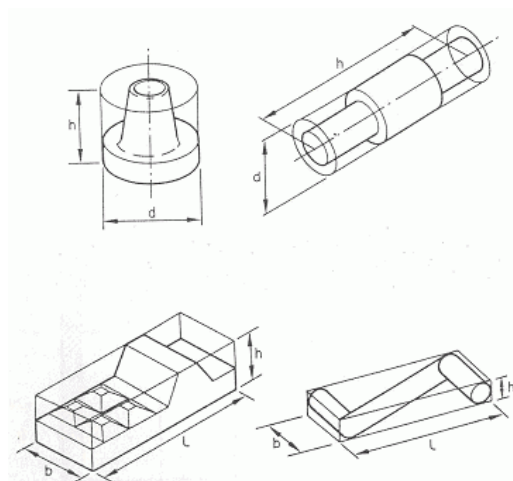
Figure 2.5 - Enveloping Shapes for Forgings

b) Forging Dimension and Weight in Forging Equipment Selection

For cost effectiveness, dies are placed in specialized standard die holders [2, 30]. The die holder dimensions and outer dimensions of forging dies are generally standardized in each plant. The die wall thickness should not be so small to

prevent from breakages during forging operation. The forging equipments have some dimensional limits for producing forgings in height and lateral axes. After estimation of the required forging force, the convenient forging line should be controlled according to the dimensional limits.

Forging equipment manufacturers define the maximum forging weight capacity of forging equipment. Forging weight is a parameter in selecting the convenient forging line.

c) Forging Material and Quantity in Forging Equipment Selection

In many of the cases of different forging materials, both hammers and mechanical or hydraulic presses can be used [31]. The contact time between the die and the metal is only slightly higher in a mechanical press than a hammer, so there is little difference in heat transfer to the dies. In hydraulic presses, the contact time is higher, therefore forging of materials that require high forging temperatures like stainless steels, heat-resisting alloys, titanium alloys is not suggested for the shortened die life. However, for materials that have poor forgability, like aluminum, hydraulic presses are preferred [26]. In hammer forging when thick sections are forged, the interior regions of the workpiece may remain undeformed. In such cases press forging must be used.

Quantity of the forging is also important to select the forging equipment. Buying cost of a press is about 4 to 6 times of a hammer [26]. The cost of producing forgings decreases as the forging time decreases. In high volume production, the presses are more economic and preferable as fewer strokes are required to finish the job. However, in low volume production presses cannot be justified against the same capacity hammers.

In presses, less operator skill is required and automation can be applied more easily like automatic handling devices and various die and forging separation mechanisms. The desired output force or the stroke of the press can be adjusted on presses during setting up of the process and the operators do not need to play with these parameters during forging. In hammers, the operator can

change the output force of the hammer. This is sometimes more advantageous for forgings, but skilled operators are required.

2.5 Forging Die Design

In closed die forging, the preform shapes are often formed to ensure proper metal distribution and flow. Preform shapes are obtained by preforming dies like fullers, edgers, rollers, flatteners, benders, splitters and blockers. The preforming impressions are done for blocking the metal to approximately its final shape, with generous corner and fillet radii. The final shape and size are imparted in the final impression. For removing the flash extensions, a trimming die is used. Thus, in closed die forging several dies are required. Open die forgings are generally made with standard flat or V swage dies.

Forging dies are designed considering; parting plane location, draft angle, fillet and edge radii, the grain flow direction, number of intermediate steps, machining allowances and webs for large holes as mentioned in Section 2.2.

The design of the forging dies is generally a matter of science and experience. Various academic studies on die design and metal flow in forging process have been done [24, 27, 28, 32, 33]. Today, some simulation and analysis programs like, MSC Superforge, Deform 3D, etc. for appropriate forging die design are available in the market. CAD programs are generally used for designing and 3-D modeling of the dies. Detailed information on forging die design process can be found in several literatures [24, 33].

2.6 Manufacturing of Forging Dies

After the dies are designed, dies should be manufactured by using various techniques. Some items related with manufacturing of dies should be analyzed further. Those items are; die material, solid modeling and NC code generation, machining the required geometry (milling, EDM, finishing) and heat treatment.

Materials of appropriately high quality like chromium and tungsten based hot work steels; H11, H13, H41 etc. are used as die material. Initial unmachined die block weight can be calculated by volumetric calculations, from material sizes large enough to enable the required tooling to be produced. The way of reducing the size of die block to its minimum practical dimensions is by making the impressions in smaller blocks to be inserted into larger standardized die holder blocks [2, 30]. When fitted to a standardized holder, the cost of die steel is greatly reduced.

Due to the die wear; periodic maintenance, remachining and replacement of the dies are required. When order quantity is small and no repeat order is expected, providing that the component material and tolerances permit, the choice of die steel should be a cheaper material as possible. If the job is repetitive using a higher grade of steel, which enhances the die life between remachining and eliminates machining time, may be more economic [2, 26, 30].

For small dies, the cost of the die material represents a minor portion of the total die costs, whereas machining cost portion is higher. The percentage cost of the die material on total die cost increases as the die size increases [31].

Die machining of hard and tough die steel is not easy and generally too much time is required on machining. Forging dies are manufactured mainly by methods like milling and electro discharge machining [3, 38].

With the increase in the use of CAD/CAM technology and NC machining, it is a common practice to produce forging dies by NC machining [24, 38]. After design of the forging dies, 3-D solid models of the forgings and forging dies may be generated by using CAD software. By using CAM software tool paths and NC milling codes may be generated.

The main die machining method is the use of vertical milling machines. The machining time in milling includes the rough or volume milling time, '$t_{volmill}$' and the finish or surface milling time, '$t_{surmill}$'.

$$t_{mill} = t_{volmill} + t_{surmill} \tag{2.12}$$

The use of numerically controlled machining tools for die machining is a common practice and exact milling time can be obtained from CAM software, during NC code generation. However, for an initial cost estimation process, milling time should be calculated for die milling cost estimation.

The rough and finish milling time can be calculated by using metal cutting formula [17, 18]. The volume of the forging should be calculated, for defining the volume of the material to remove. Surface area of the forging is required to be calculated, for obtaining the machining surface area.

$$t_{volmill} = V_0 / Z_v \qquad (2.13)$$

$$Z_v = a_e * a_p * V_f \qquad (2.14)$$

$$t_{surmill} = S_0 / Z_s \qquad (2.15)$$

$$Z_s = a_p * V_f \qquad (2.16)$$

where, V_0 = volume of material to remove in mm^3

S_0 = surface area of the material to remove in mm^2

Z_v = metal removal rate in mm^3/min

Z_s = surface rate in mm^2/min

a_e = depth of cut in mm

a_p = tool path interval (lateral depth of cut) in mm

V_f = feed speed in mm/min

The calculated machining times are approximate, because the formulation does not include the time spent for the rapid movements of the tool. It is suggested to add a 15% percent additive time for correction from statistical methods [19].

$$t_{mill} = 1.15 * (t_{volmill} + t_{surmil}) \qquad (2.17)$$

Using very small diameter cutting tools (diameter $\leq$ 4 mm) on hard die material for machining small cavities on dies and using ball-end edge machine cutting tools for surface finishing on hard die material is not economically and technically feasible [2]. The methodology for surface finishing and machining small cavities is using the electric discharge machining (EDM) technology. EDM is a method for manufacturing cavities by means of the controlled removal of material through melting or vaporization by high-frequency electrical sparks. EDM electrodes, which are the negative geometries of the desired machining volume, are generally machined from graphite or copper.

Some types of other machines like shapers, lathes, WEDM machines and manual-milling machines may be required for manufacturing of the dies. Hand finishing on dies like grinding and polishing is generally required for finishing.

Heat treatment of dies is done to improve the die life. Heat treatment methods depend on the die material, size, weight and expected properties. Therefore, details of heat treatment may vary considerably [26]. Heat-treating includes many steps like normalizing, annealing, stress relieving, preheating, austenizing, quenching, and tempering. Details of the die heat treatment procedure may be seen in several literatures [24, 26, 29].

2.7 Heating of the Forging Billet and the Heating Equipment in Forging

The forging billets are heated up to very high temperatures generally between 1200 ^{0}C –1300 ^{0}C. Heating is achieved by use of oil, gas, electric and induction furnaces for hot forging process.

The oxidation in the atmosphere results in scale formation as discussed in Section 2.3. To decrease scale formation, atmosphere should be controlled inside the furnace. Too little air results in inefficient heating and too much air reduces heating efficiency and results in excessive scale formation. Generally, furnace chamber is fed with an air supply from a fan or blower [30].

Furnaces may be batch or continuous type. Batch furnaces are usually loaded and unloaded manually by hand and heating time is determined by furnace operator on the basis of measurements or empirical guidelines. Continuous furnaces provide mechanical means of feeding the stock through the furnace and provides greater assurance of uniform heating [26].

The box furnaces are the simple batch type furnaces, which are fired with oil or gas. The box furnaces consist of a box-form chamber made from refractory bricks and supported by steelwork. The box type furnace is compact, which makes it to be accommodated in positions best suited to the operator close to the press or hammer. Its straightforward mechanism and construction results in small initial cost and maintenance cost. Application of gas is easier to balance the fuel and air mixture for decreasing scale formation.

Rotary-hearth furnaces are widely used furnaces, in which hearth can be rotated in either direction by means of a drive mechanism. The hearth rotates bearing the stock from the cold zone and through a heating section at a predetermined rate. Hearth speed is regulated for heating stocks during one rotation to obtain uniform heating times, without the necessity of regular loadings [26]. Rotary furnaces have cool loading area and gives comfortable loading conditions for operators. Heating can be done by gas, oil or electricity.

Pusher furnaces generally have a tunnel like chamber, at one end of which billets are pushed along the hearth mechanically through the heating zone to exit from a door at the opposite end [23]. Control of the pusher may be automatic or manual. Heating can be done by gas, oil or electricity.

Induction furnaces are efficient and economical methods of heating the forging billets [20]. Forging billets are heated by use of electricity flux, which penetrates inside the material. Lower frequency electricity penetrates inner sides of the billet with the greater depth of flux, therefore larger workpieces require lower frequencies. Induction furnaces are built in variety of sizes. In Figure 2.6 a sample induction-heating furnace is shown [23]. Generally, induction heaters are automated to provide continuous supply of the heated stock. Accurate temperature

control, less scale formation, automated easy operation, cleaner working conditions and high heating efficiency are the advantages of induction heating. However, initial capital investment is high.
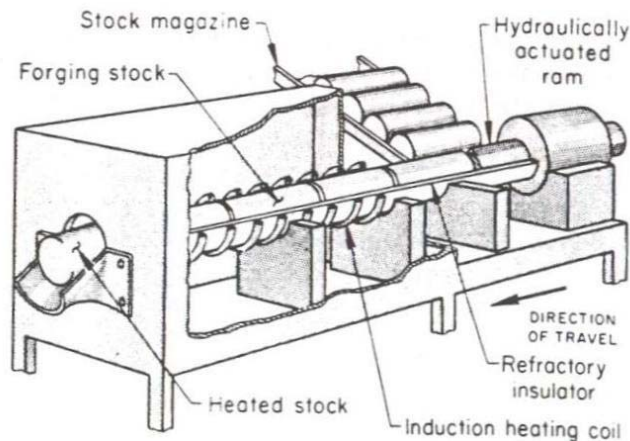
Figure 2.6 - Induction Heating Furnace [23]

2.8 Secondary Operations in Forging

Secondary operations are required to bring the forging to the required surface finish, shape, precision and mechanical property. Secondary operations includes; cleaning, shot-peening, heat treatment, coating and painting.

Scale or iron oxide removal from forgings is important, because cutting tools used in machining have a shorter life if they are used to machine surfaces covered with scale. Scale has a tendency to separate and mix in lubricating oil and this may create big problems in bearings, engines and other critical elements in machines. Scaled surfaces prevent successful painting and coating.

It is preferred to minimize the scale formation and remove the scale before the forging billet is put into the die. The scale falls off during hammering or squeezing between the forging dies and blown away by applying compressed air.

If there is any remaining scale on forging, it should be removed by using some cleaning operations like: pickling, tumbling and blasting. Acid pickling and then sandblasting is the most widely used procedure for flash removal[23].

• *Pickling* is a cleaning process in which forgings are left in an acid bath. The acidic solution loosens the scale and removes it from the surfaces. Generally %12-15 percent concentrate of sulphuric acid and an inhibitor to protect clean metal surfaces from acid is used as acid bath. The acidic bath is maintained at recommended temperatures, which depends on the material type. Pickling process is best suited to nonferrous forgings like copper, brass and aluminum [29]. Pickling process can be automated by conveyor systems, which makes it suitable for continuous processing.

• *Tumbling* is a cleaning process in which forgings are rotated or tumbled in a tumbling barrel, which holds some type of loose abrasive mostly coarse sand or small particles of metal. The tumbling barrel is rotated at slow speeds and the forgings and abrasive particles are rolled over themselves and scale is loosened and separated from forgings. The tumbling process also relieves some of the stresses formed during previous operations by peening effect of small particles. Sharpe edged forgings may be damaged by tumbling process; so some other type of cleaning process should be applied on such products. Maintenance costs are low, but operational time is greater than other methods [30].

• *Sandblasting* and *metallic-shot blasting* are cleaning processes in which special machines are used for directing and blasting a jet of sand or metallic-shot against the forgings. The blasting power is supplied by compressed air. The abrasive jet of sand or metallic-shot cleans the scale from forgings. The blasting process is an effective and rapid method, especially used in high volume productions of small and medium sized forgings. Smooth surface finish on forgings can be obtained by blasting.

There are some other types of secondary operations processed to increase the usability and quality of forgings.

- *Shot Peening* is a cold working method applied by throwing round metallic shots at high speeds on forgings. The shots produce a local surface compression, greater than the corresponding tension stresses developed interior of the sections [29]. Shot peening increases the fatigue life of the forgings. Surface of the forging is strengthened and hardened by shot peening.

- *Heat Treatment* is a process that is done to harden the parts and removing the internal stresses that might occur during the forging process. Generally, forgings can be used without further heat treatment as process of forging includes a certain amount of heat treatment itself. However, for maximum usefulness in high strength requirements, special heat treatment procedures may be required. Heat treatment procedure requires some specialized furnaces for heating and cooling the forgings under control. Heat treatment process is generally done in specialized firms. Details of forging heat treatment can be seen from literature [24, 26, 29].

- *Coating and Painting,* operations may be desired by the customer for visuality, for improving surface quality, protection from corrosion and surface wear. Generally, phosphate or zinc surface coatings and some special paintings may be applied on forgings.

2.9 Quality Control in Forging

Quality of a product means its conformance with a prescribed standard. Quality assurance results from using suitable inspection procedures to establish reliability. Reliability is the probability that a product will perform its intended function for a specified time, under stated operating conditions. Manufacturing high quality products is the main objective for many companies. Especially in forging industry, quality is very important, because forgings are generally used in high strength and reliability required applications where tension, stress, load, and human safety are critical considerations.

Quality control and inspection process includes all the controls from selection of raw material to final heat treatment to satisfy all the requirements for

metallurgical integrity, mechanical properties and dimensional accuracy. Common defects in forgings like openings, fractures, laps, flakes etc. inside and surface of the material are due to initial defects in raw materials, improper forging, heating and cooling. It is difficult to detect the defects, unless they are on the surface and of such size that can be seen with naked eye [29]. Various methods are devised to aid the inspection of forgings; microscobic control, deep etch test, up-end test, hardness tests, impact tests, penatrant testing, etc. Details of forging inspection processes can be seen from several literatures [24, 31, 29]. For some forgings, special more costly quality testing like nondestructive testing methods may be desired by the customer. Non-destructive testing is an important tool ensuring that the forgings are good quality. Details of non-destructive testing can be obtained in several literatures [24, 39].

Forgings should be controlled dimensionally by using measuring apparatus. For some cases, coordinate measuring machine should be used. Die wear, which produces dimensions outside the tolerance, should be under control. The initial test runs and approval of the first forgings are under the control of quality control section.

Generally, quality control department in a company collect and report the costs that occur due to product quality control. A quality costing system monitors and accumulates the costs incurred by a company in maintaining or improving product quality. There are four categories of costs associated with the quality programs that several firms have found useful [10].

- *Preventation costs* focus on preventing the production of products that do not conform to quality specifications. Costs that can be grouped under this category are; employee training, tool design reviews, machine tooling calibration.

- *Appraisal costs* focus on detecting the unquality products, which do not conform to the specifications. Costs that can be grouped under this category are; inspection and testing programs for raw materials and products, usage of special quality control and measurement equipment like coordinate measuring device,

nondestructive testing devices, engineering programs like statistical quality control processes.

- *Internal failure costs* focus on costs incurred when an unquality product is detected before its shipment to customers. Costs that can be grouped under this category are; rework costs, scrap costs, tooling changes and downtime costs.

- *External failure costs* focus on costs incurred when an unquality product is detected after its shipment to customers. Costs that can be grouped under this category are; mainly the customer unsatisfaction created by the defective products, loss of potential future sales, back shipment costs and all of the costs incurred in internal failure costs.

The cost of initially developing and maintaining a company quality costing and internal reporting system is high. However, by using an internal quality reporting system, the trends in costs of quality can be monitored, quality decreasing items can be analyzed and solution methods can be studied, the increased cost and importance of quality can be communicated to all members of the organization by reports. Having a cost accounting system that regularly monitors on quality costs is very important and many companies have prompted to install quality-costing systems [9].

2.10 Packaging and Transportation

The packages and transportation containers must be adequate to prevent deterioration of supplies and damage due to the hazards of shipping, handling, and storage. Transportation containers are generally huge chests that can carry many forging products, which are limited by the maximum weight carriage capacity.

Transportation incoterms or transportation terminology have not been universally accepted, but the International Chambers of Commerce (ICC) attempt to establish a standardized common language for transportation terminology in the year 2000. The definitions of some frequently used transportation incoterms are given below [37].

a) Ex-Works (EXW); means that the seller's only responsibility is to make the goods available at his own factory. The seller is not responsible for loading the products on vehicles provided by the customer. The customer takes the full cost and the risks involved in taking the goods from the seller's factory to their destination. The term EXW represents the minimum obligation of a seller.

b) Free On Board (FOB); means that the seller's obligation is to place the products on board of a ship at the port named in the sales contract. The risk of loss or damage to the products is transferred from seller to the customer when the products pass the ship's rail.

c) Cost & Freight (CFR); means that the seller's obligation is to pay the costs and freight necessary to transport the products to the named destination, but the risk of loss or damage to the products is transferred to the customer when the products pass the ship's rail. This term is used for waterway transportation. The equivalent term used for transportation other than ship is *Carriage Paid To (CPT).*

d) Cost, Insurance and Freight (CIF); means that the seller's obligation is to pay the costs and freight, necessary to transport the products to the named destination, and also obtain insurance to the risk of loss or damage to the products. The insurance level obtained by the seller is minimum cover, if the customer desires higher cover levels, this should be agreed with the seller in sales contract. This term is used for waterway transportation; the equivalent term used for transportation other than ship is *Carriage, Insurance Paid To (CIP).*

CHAPTER 3

FORGE VOLUME ESTIMATION METHOD AND SOFTWARE MODULE

3.1 Forge Volume Estimation

Determination of the forge volume and the forge weight is very critical to find the required press or hammer capacity, flash allowance, scale loss, billet weight and the forging material cost. The forging material cost is the most important cost item in forging cost estimation.

In general practice, the forge volume and weight can be obtained one of the four ways;

1) Forge weight is sometimes stated by the customer.

2) Customer may send a sample forging. Forge weight can be found by weighing the sample forging.

3) Customer may send a 3-D CAD model of the forging. The forge volume and weight can be calculated by using CAD software.

4) The forge volume is required to be calculated by the cost estimator, for the cases when only a 2D technical drawing is sent by the customer and no information about the forging volume and the forging weight is available.

For the first case, the forge weight should be controlled by calculating the volume and the weight of the forging from the provided technical drawing. For the third case, unless both the customer and the forging company use the same CAD software, 3-D CAD model is sent in IGES Initial Graphics Exchange Specification) format. IGES CAD model must be generally repaired to calculate
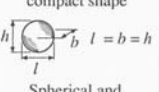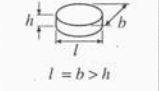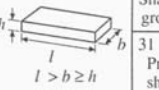
the volume, which may take some amount of varying times. Obtaining and using CAD software may not be economically feasible for the small and medium sized forging companies, because obtaining a CAD software and training CAD personnel is expensive. Around 90% percent of the cases, the forge volume and the weight should be calculated by the cost estimator [2].

Therefore, in this thesis study, a volume estimation software is considered to be developed to ease the work of the estimator.

For forge volume estimation, the method suggested by Sabroff is breaking down the forging part into simple shapes for easy volumetric calculations [31]. It is stated that, cross sections other than the basic geometrical shapes can be closely matched to one of the basic geometries by further division and separations. The errors arising will be small as to be of little consequence. Sharman suggested the same methodology and usage of standard tables including volumes of very basic geometries like square, round bars and spheres [30]. In industry, some volume formulations and tables are used to calculate the forge volume [2].

To observe common forging shapes and possible basic geometries, forging shape classification systems have been analyzed. In literature, there are various forging shape classification and coding systems, which are prepared for classification and grouping of forgings according to their shape.

Spies classified forgings into three main groups as compact shapes, disc shapes and elongated shapes, which contains subgroups and subsidiary elements as shown in Figure 3.1 [35]. Compact shapes have three major dimensions as length, width and height, which are approximately equal. The disc shapes have two dimensions as length and width, which are nearly equal to each other and larger than the height. Studies show that 30% percent of the forgings can be classified in this group [36]. Elongated shapes have one dimension that is significantly greater than the other two.

Figure 3.1 - Spies Classification System [35]

Knight classification system categorizes the shape of the forgings in similar to Spies with somewhat more detail as compact, flat and long parts [36]. Forgings are classified into ten basic shapes considering the dimensions as compact parts where length, width and height of the forging are equal in length (L=B=H); flat parts where length is equal to width and greater than height of the forging (L=B>H) and long parts where length is much greater than width and height of the forging (L>>B,H). Flat parts are sub grouped as disc like, rectangular or polygonal plan, irregular plan, open rings, cross arm and long parts are sub grouped as short, medium, long and very long.

The classification system of Knight is expanded and integrated into "Design for Forging Handbook", which attempts to classify and design the forging more systematically by considering various group of parts [40]. In this system, materials have been divided into ten basic groups as compact parts, flat parts and long parts, which are shown in Figure 3.2. In this system, classification is more systematic and detailed compared with the previous systems. A similar more specialized study is done by Gökler, for upset forgings [41].

0	Compact parts $L/B \leq 3/2$, $L/H \leq 3/2$ (1)		
1	Flat parts $L/B \leq 3/2$ $L/H > 3/2$ (1)	Round (disk-like) parts (2)	
2		Non-round parts (2)	
3	Long parts $L/B > 3/2$ (1)	Longitudinal axis of part straight (3)	$L/B \leq 3$
4			$3 < L/B \leq 8$
5			$L/B > 8$
6		Longitudinal axis of part bent or curved in one plane (3)	$L/B \leq 8$
7			$L/B > 8$
8		Longitudinal axis of part bent or curved in more than one plane (3)	$L/B \leq 8$
9			$L/B > 8$

Figure 3.2 - Design for Forging Handbook Classification System [40]

A wide range of products, which may have very different shapes, can be produced by forging process. After analysis of the forging classification and coding systems; at second step various forgings have been examined for analyzing the forging shapes and defining possible basic geometrical elements. Some of the examples for the forgings are shown in Figure 3.3.

Figure 3.3 - Various Examples for the Forgings

3.2 Volume Estimation Software "*Easy-Volume*"

In this study, the method used for estimating the net weight of the forging, is fragmenting the forging into simple basic geometrical shapes for easy volumetric calculations. Simple shape volumes can be calculated and summed up to give the volume of the forging. In Figure 3.4, application of volume fragmentation method on two simple forgings is shown. In Figure 3.5, application of volume fragmentation method on a more complex forging is shown.

Figure 3.4 - Application of Volume Fragmentation on Simple Forgings

Figure 3.5 - Application of Volume Fragmentation on a Complex Forging

In this study, by using volume fragmentation methodology, a new system for speeding up and simplifying the forge volume estimation process have been developed. This system is named as "EASY-VOLUME". After analysis of forging classification and coding systems, examination of various forgings and associative studies with the forging industry; 24 primitive elements, including

simple geometrical shapes and some more complex shapes, are formed to speed up and ease the volume estimation process. The primitive elements are shown in Figure 3.6. Primitive elements include; rectangular prism, triangular prism, polygon prism, pyramid, irregular pyramidal shape, cylinder, cone, torus, annulus, recta circle, elliptic cylinder, elliptic cone, elliptic torus, circular cone, circular segment, sphere, spherical segment, spherical zone, truncated spherical shell, elliptic corner prism, rectangular cross section fork, circular cross section fork, circular fork zone and crescent fork. Parameters and details for each primitive element of the *Easy-Volume* system are given in Appendix D. Also, more specific elements may be added to the system according to the requirements of the different forging companies. At the moment, 2 special parametric elements shown in Figure 3.7 are added to the system.
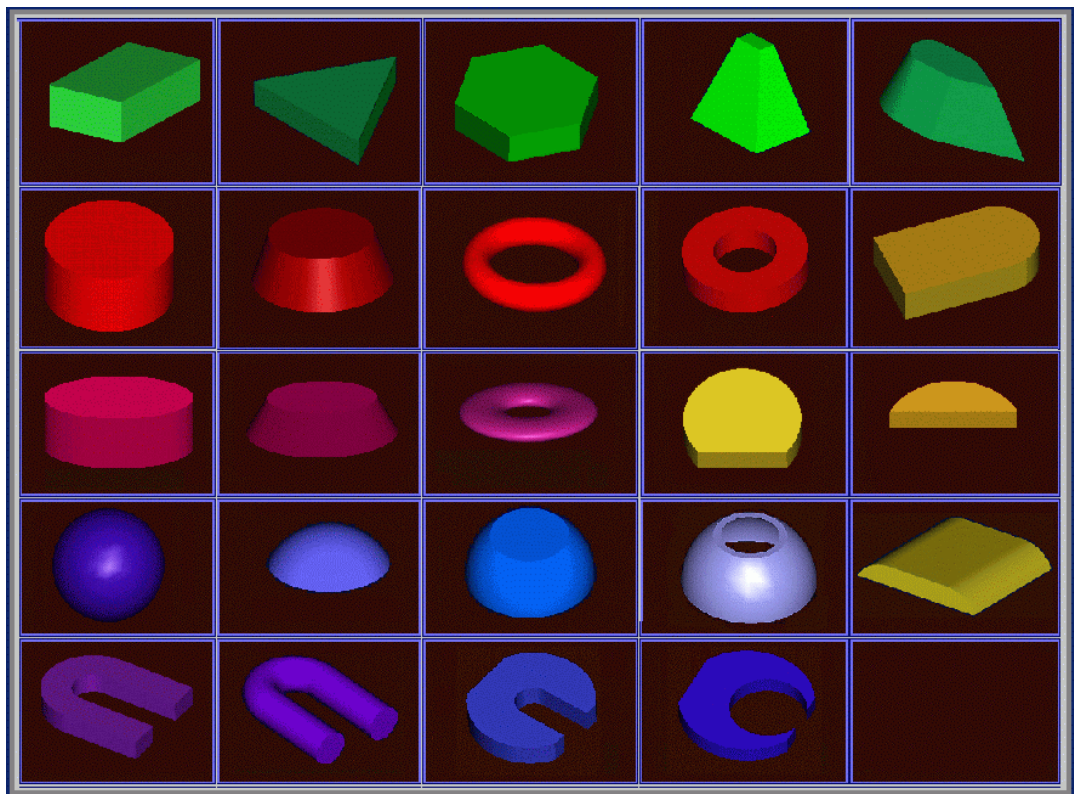
Figure 3.6 - Primitive Elements
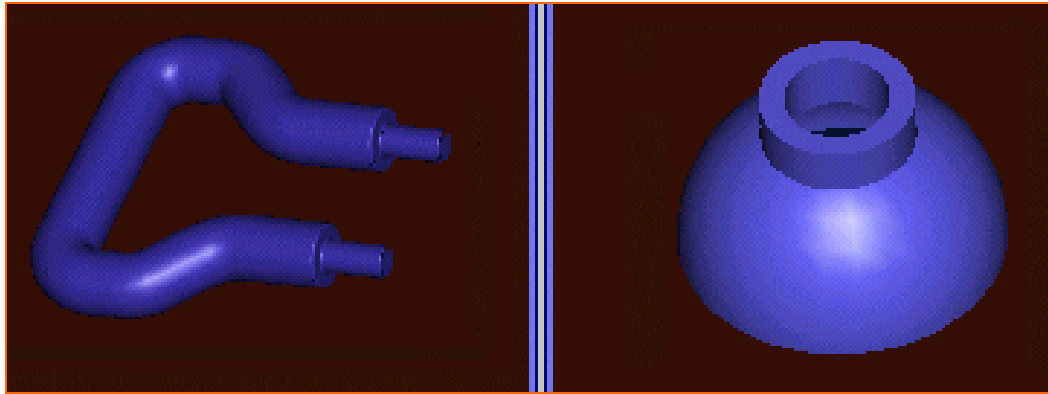
Figure 3.7 - Special Parametric Elements

The software makes it possible that the same primitive elements can be used up to 20 different cases, in a particular volume estimation process.

3.3 Case Study by using Easy-Volume

The selected part for the case study of volume estimation process by using *Easy-Volume*, is coded as AK131 9.104.12.C20-1. The required forging product is shown in Figure 3.7 and 3.8. The technical drawing of the forging sent by the customer is shown in Figure 3.10. Forging material is SAE 4140 with a density of 0.00786 g/mm^3 .

The forging is fragmented into a spherical segment, a cone, a rectangular prism and two smaller circular segments subtracted from two circular segments as seen in Figure 3.11. The required dimensions are obtained from the technical drawing. In cost estimation software, by using *Easy-Volume* volume estimation system, the dimension data are input to the defined primitive elements as shown in following Figures 3.12 - 3.15. The resulting forge volume and the forge weight is shown in Figure 3.16

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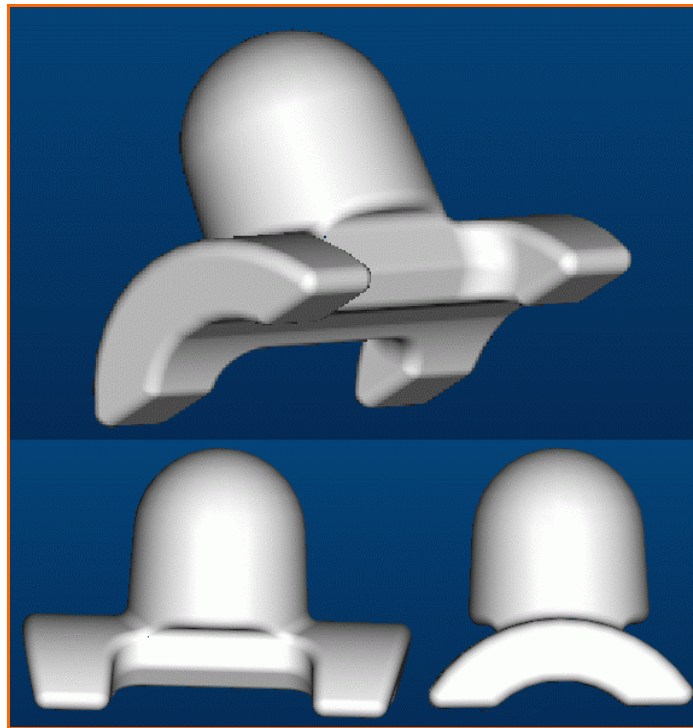
Figure 3.8 - View of the Sample Forging

Figure 3.9 - Photograph of the Sample Forging
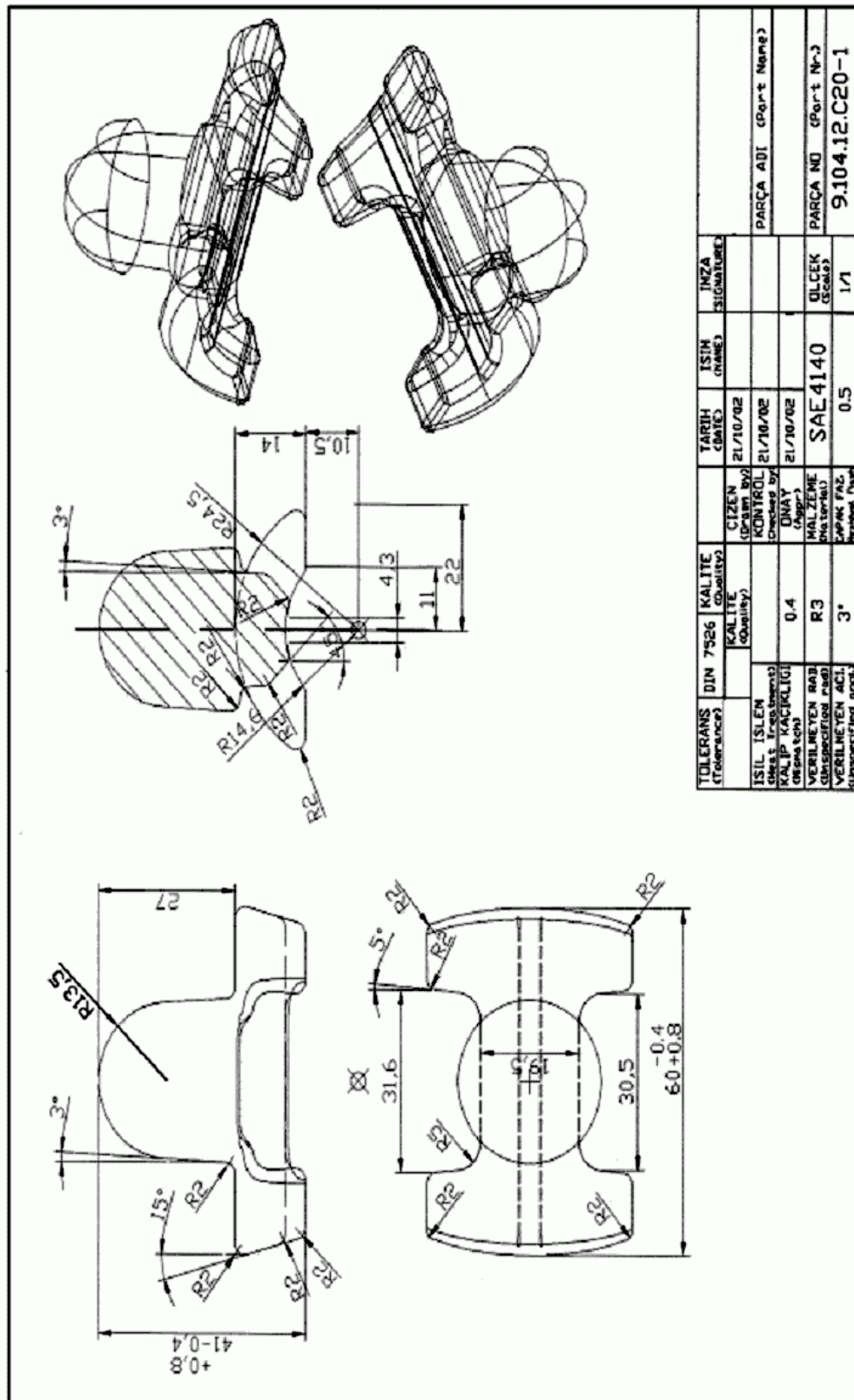
Figure 3.10 - Technical Drawing of the Sample Forging
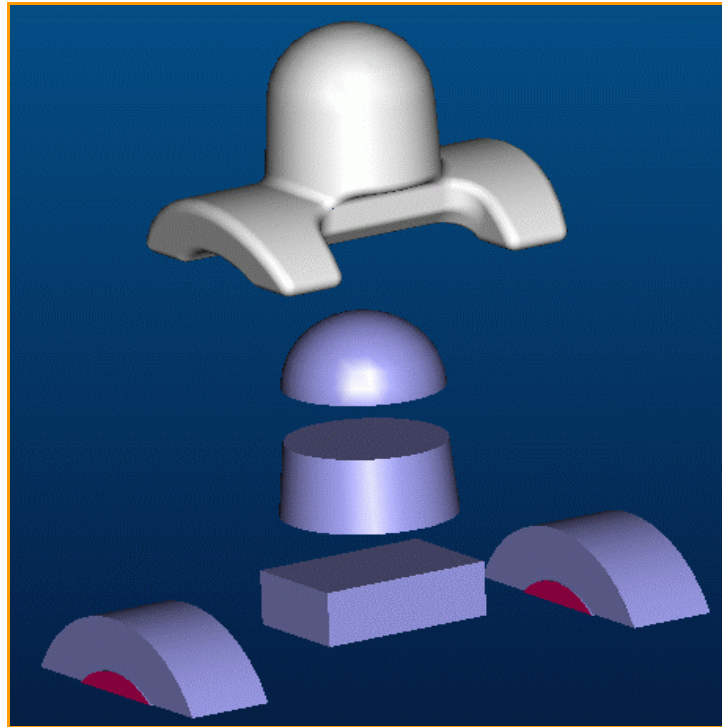
Figure 3.11 - Schematization of Volume Fragmentation Process
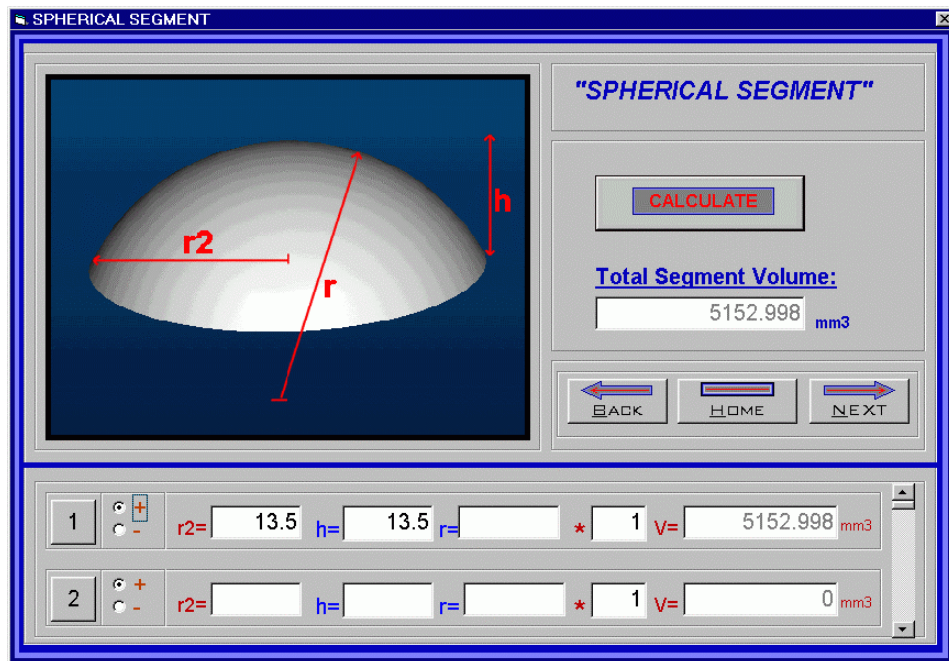
Figure 3.12 - Spherical Segment Primitive Element
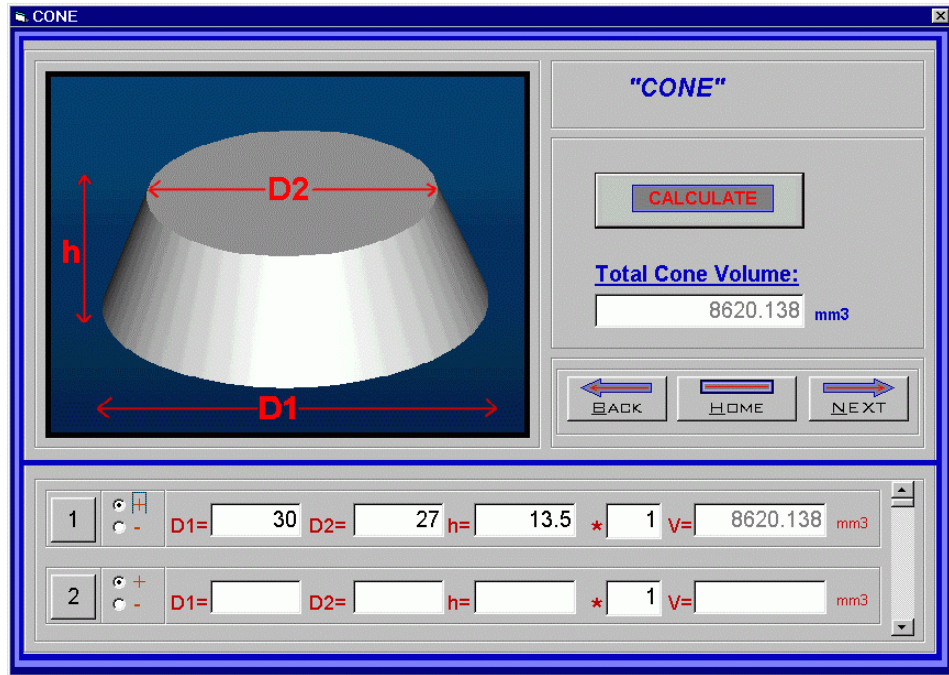
Figure 3.13 - Cone Primitive Element
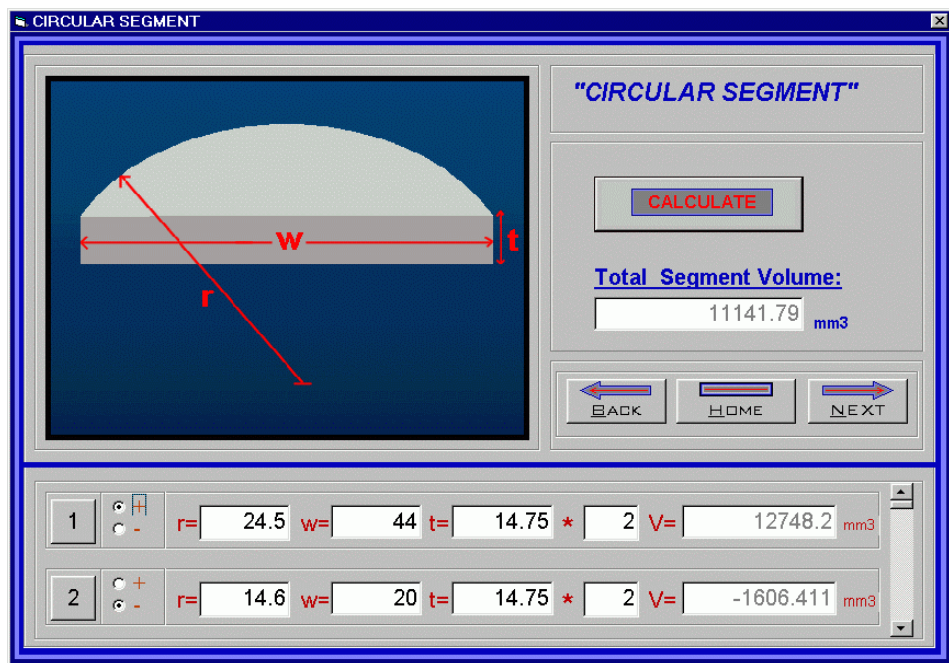
Figure 3.14 - Circular Segment Primitive Element
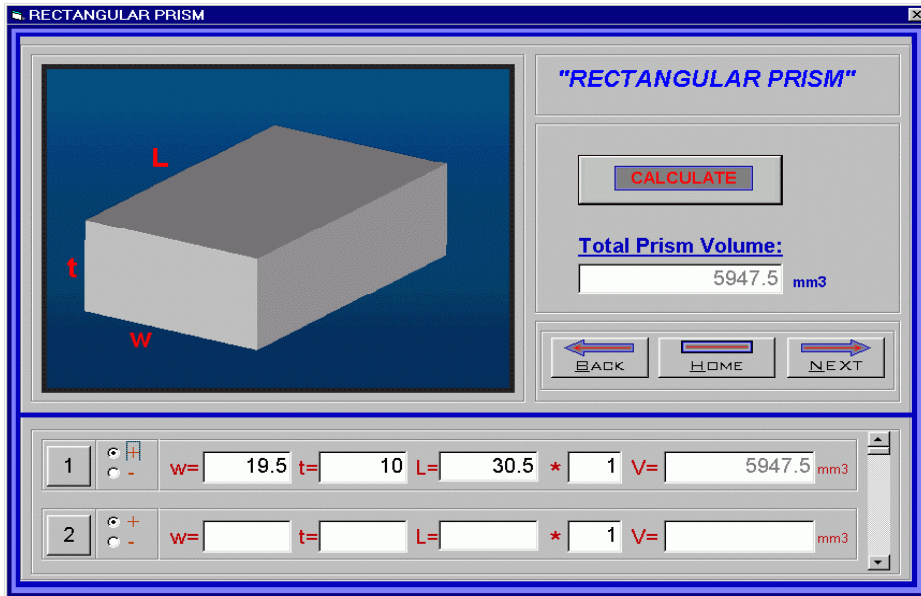
Figure 3.15 - Rectangular Prism Primitive Element
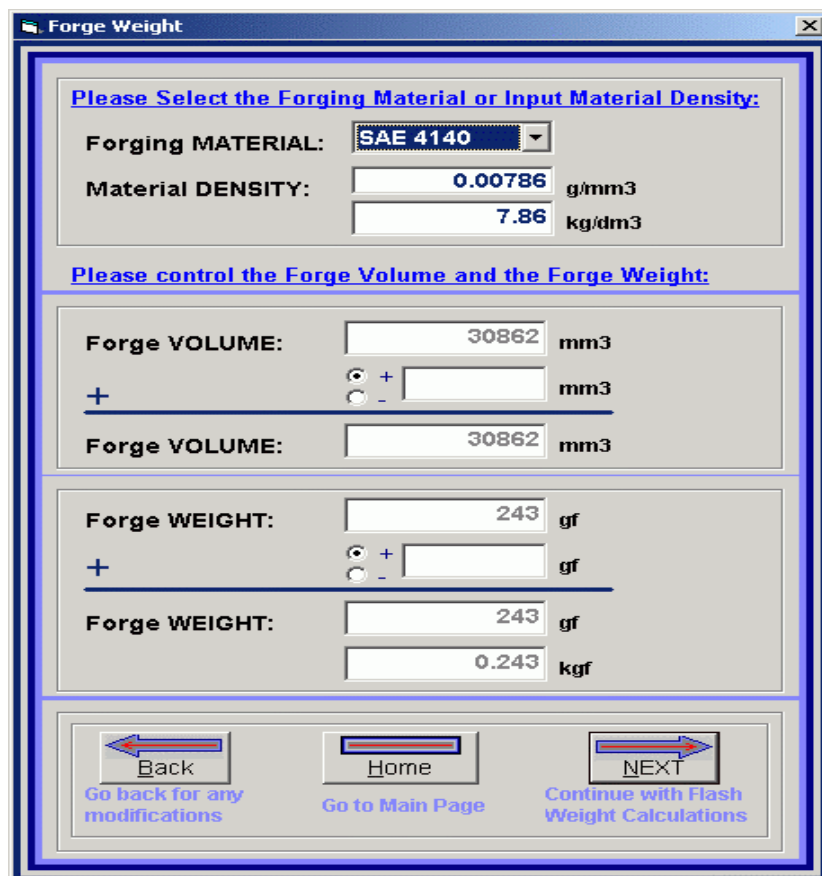
Figure 3.16 - Forge Weight Result

To check the result, 3-D model is prepared in CAD software and by using CAD software, the volume of the sample forging part is found to be 29300 mm^3 and the forge weight is found to be 231 g. By using *Easy-Volume*, volume of the forging is found to be 30862 mm^3 and the forge weight is found to be 243 g., which results in an error of %5.2. The result is satisfying and seems convenient.

3.4 Sample Forge Volume Estimation Results

Results of sample forge volume estimation processes by using *Easy-Volume* volume estimation system on various forging parts are shown in Table 3.1.

According to the calculated 20 sample forging part volumes, the average of the absolute errors is found to be 4.5%. During volume calculations, it has seen that good accuracies on forging volume estimations are obtained without a great effort. Theoretically, if the forge volume is divided into smaller and smaller calculable volumes, the total summed forge volume should be found with a very small error, very close to the real volume. However, the cost of a very detailed process will be high considering the time spent on such kind of a volume fragmentation process. The resulting accuracy should worth the effort. Generally, with convenient approximations on fragmented volumes, the forge volume can be found in short periods with a reasonably good accuracy. By using the *Easy-Volume* system, forge volume calculation is speeded up and made easier, with the computational capacity of the computer.

Table 3.1 - Sample Forge Volume Estimation Results

Forging Code	Forging Name	Real Results Volume (mm³)	Mass (g)	Software Results Volume (mm³)	Mass (g)	Error (%)
AK 2	2_00_98_353 Gabel	868000	6950	881723	7054	1.5
AK11	36779/1 D2 Sleeve Yoke	317000	2536	320022	2560	1
AK29	0 367-35 82822 Ç	2133761	17070	2223132	17785	4
AK33	0000079H Smeed tekening excenter	408756	3270	426491	3412	4.3
AK36	RK-50 schellensegment	63343	512	60511	484.1	-5.4
AK40	655.100.000	65190	522	68834.6	550.7	5.5
AK77	Lift-Ball M20	41286	330	36756	294	12
AK81	13018781	1188000	9084	1137249	9098	-0.2
AK84	341.090-0117 Zylinderboden	356000	2850	374161	2993	5
AK86	Y 150309	122704	9816	126288	1010	9
AK87	Y 300122	100271	802	112242	8989	11.2
AK88	HIJSDOG 1 TSVLA	9660	773	90528	724	-6.2
AK89	255x53 Coopra HIJSOOG 1	5030	400	48555	388.4	-3.4
AK92	Y 154393.02	226498	1811	222582	1781	-1.7
AK109	00.05.0643	179551	1436	189387	1515	5.5
AK110	H343304800	1107195	8858	1070773	8566	-3.3
AK112	46262 M20	195492	1564	202340	1618	3.5
AK115	0202/065/0F	1304984	10440	1321802	10575	1.2
AK129	SP 212 5366	1259474	10080	126650	10132	0.5
AK131	9.104.12.C20-1	29300	230.3	30862	242.6	5.3

CHAPTER 4

FORGING COST ESTIMATION METHODOLOGY

4.1 Forging Cost Items

The cost for producing forgings depends on many factors, such as material, die, labor, equipment, inspection, heating and overhead costs etc. These charges may vary from plant to plant and also from product to product with in an individual plant [24]. The items that form up forging cost can be grouped as:

1. Material cost

2. Forging equipment cost

3. Tooling cost

4. Labor cost

5. Overhead cost

6. Billet heating cost

7. Secondary operations cost (cleaning, heat treatment, inspection, etc.)

8. Quality control cost

9. Packaging and transportation cost

Hobdel and Thomas [36, 42] surveyed costs for several plants and forgings produced by the closed die hot forging process, and obtained the diagram shown in Figure 4.1. According to their survey, the cost of raw material generally comprises about 50% of the total cost of the forging. Labor cost, overhead cost and forging equipment cost comprises about 30%. Tooling cost and secondary operations cost each comprises about 10% of the total forging cost.
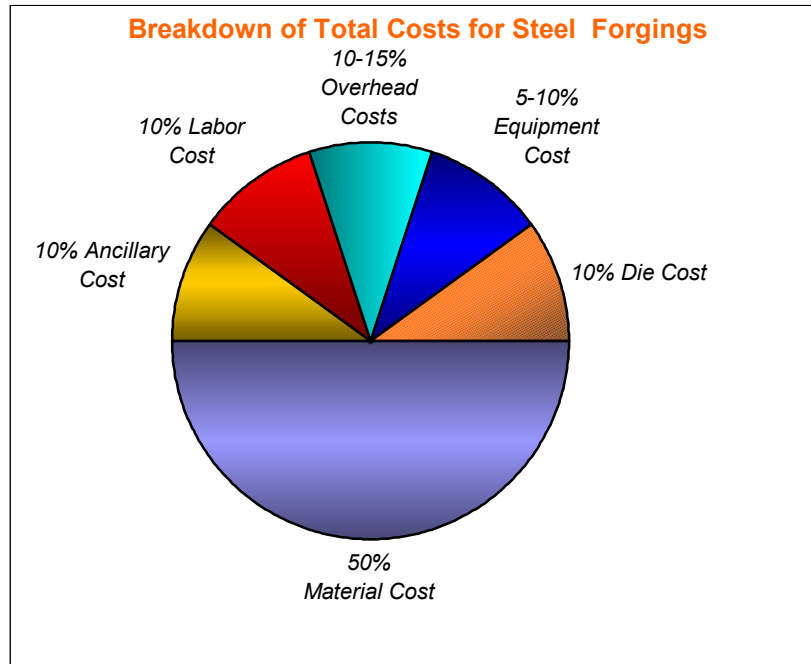
Figure 4.1 - Breakdown of Total Costs for Steel Forgings

4.2 Selection of the Forging Cost Estimation Method

When choosing an estimation methodology, the estimator must always remember that the type of the cost estimation method used will depend on the adequacy of product definition, level of detail required, availability of data, and the time constraints. No matter which estimation technique is used, the estimator must ensure that the cost estimate completely defines the process and is technically reasonable [8]. The selected method should be complicated to include all applicable cost items. The selected method should be valid and consistent, capable of providing logical, reproducible results [3].

In real life, each industry develops its own form of cost estimation that is most appropriate to its own environment. In forging industry, the estimation by analogy and the bottom-up estimation methods are common.

FORGING WORK BREAK DOWN STRUCTURE (WBS)

FORGING PRODUCT

LEVEL

1

2 — Material Cost | Equipment Cost | Die Cost | Labor Cost | Overhead Cost | Heating Cost | Secondary Operations Cost | Quality Control Cost | Shipment Cost

3

Material Cost:
- Forge Material Cost
- Waste Material Cost

Equipment Cost:
- Depreciation Cost
- Operating Cost
- Set Up Cost
- Maintenance & Repair Cost

Die Cost:
- Die Material Cost
- Design Cost
- 3-D Modelling NC Code Generation
- Heat Treatment Cost
- Machining Cost

Overhead Cost:
- Factory Overhead Cost
- Indirect Labor Cost
- Indirect Material Cost

Secondary Operations Cost:
- Pickling Cost
- Tumbling Cost
- Sand Blasting Cost
- Shot Peening Cost
- Heat Tratment Cost
- Painting Cost
- Coating Cost

Quality Control Cost:
- CMM Cost
- Process Control Cost
- NDT Cost

Shipment Cost:
- Package Cost
- Transportation Container Cost
- Transportation Cost

4

Waste Material Cost:
- due to Flash Loss
- due to Saw Cut & Bar End Loss
- due to Tonghold Loss
- due to Scale Loss
- due to Die Wear Loss

Machining Cost:
- Die Milling Cost
- EDM Machining Cost
- EDM Elctrode Milling Cost
- Other Machining (Lathe, Planer, W/EDM....)
- Hand Machining Cost

5

Die Milling Cost:
- Depreciation Cost
- Operation Cost
- Operator Cost
- Tool Cost

EDM Machining Cost:
- Depreciation Cost
- Operation Cost
- Operator Cost

EDM Elctrode Milling Cost:
- Depreciation Cost
- Operation Cost
- Operator Cost
- Tool Cost

Other Machining:
- Depreciation Cost
- Operation Cost
- Operator Cost

Hand Machining Cost

Figure 4.2 - Forging Work Break Down Structure (WBS)

58

Of the four cost estimation methods presented in Section 1.3, use of the bottom-up estimation method seems more reasonable. The bottom-up estimation method gives the most reliable and accurate results. However, application of the bottom-up cost estimation method might be complex and time consuming, as too many detailed calculations are required. Using computer aided estimation software may simplify the complexity of the method and shorten the estimation time. In this thesis study, as the forging process is well defined and a detailed 'work breakdown structure' can be developed, the bottom-up cost estimation method has been used.

To apply the bottom-up cost estimation method, forging work break down and cost structure is prepared considering the forging process and the cost items. Work break down and cost structure is shown in Figure 4.2. The items that form up forging cost will be analyzed in the following sections.

4.3 Forging Material Cost

Production materials are separated into two as direct and indirect materials. Direct materials are the materials used in the manufacturing process that become a significant part of the finished goods. For forging process, the forging material is the direct material.

Indirect materials are the materials used in manufacturing process that are minor in amount or cannot easily be allocated to a specific product. Some indirect materials, which do not become a part of the finished goods, are generally called operating supplies. Some examples for the forging process are cleaning supplies used in the factory, oil used for lubricating the dies and forging equipment, etc.

The recording and computing of indirect material costs are very hard and require a great amount of time. Therefore, indirect material costs are generally considered as overhead costs.

In forging process, it is convenient that the material cost is the cost of material required per forging including the waste material. This will include;

- net weight of the forging (forge weight),

- waste material due to scale loss,

- waste material due to flash,

- waste material due to saw cut (cutting scrap) and bar end loss,

- waste material due to tong hold loss,

- waste material due to die wear.

The weight of the forging including the waste material is called 'forging weight'. After removal of the scale, trimming off the flash and tong hold; the resulting net weight of the final forging product is generally called 'forge weight'.

Material cost is the most important cost item in forging cost estimation as it comprises about half of the total forging cost as discussed previously. In this study, for determining the net weight of the forging; "*Easy-Volume*" volume estimation system, which is introduced in Chapter 3, has been used.

For estimation of waste material weight due to scale loss, recommendation of Bruchanow and Rebelski, which is summarized in Table 2.1, has been used throughout this study.

For flash weight estimation recommendation of "National Association of Drop Forgings (NADF)", which is shown in Table 2.2, has been used.

Tong hold loss may be calculated or it can be assumed to be a percentage of the forge weight. In cost estimation software, tong hold loss is approximately estimated as a percentage of the forge weight.

The waste material due to saw cut depends on the saw thickness and the billet diameter and it should be calculated for a detailed cost estimation. However, at the initial cost estimation process, going into such level of detail will not pay the effort that is spent. The procedure that can be used, may be considering the bar-end waste and the saw-cut waste material weight as a percentage of the forge weight. Suggestion of Sabroff, which was explained in Section 2.3 that the bar end waste material weight is about 5% of the net forging weight, is applicable.

If the waste material due to die wear will be considered, an approximation of 4% of the forge weight is applicable, as stated in Section 2.3.

4.4 Forging Equipment Usage Cost

Forging equipment usage cost is the cost of using the forging equipment to produce a forging. Forging equipment usage cost can be calculated by the general formulation,

$$K_P = C_P / P_R \qquad\qquad (4.1)$$

where, C_P : the equipment usage cost per unit time (\$/time),

P_R : the production rate (pieces/time).

Generally, unit time in the formulation is chosen to be hour so thus, the forging equipment cost is the hourly cost of the forging equipment usage divided by the number of forgings produced per hour.

Forging process requires a few numbers of machines. Most basically, a heating furnace, a great capacity press or hammer and some smaller presses for preforming, trimming and punching operations. Those equipments together are named as '*forging line*'. The equipments in a forging line are placed near to each other. The forging line is named with the greatest capacity press or hammer name in the line, in which the final impressions are done, for example, '4000 tonf hydraulic press line', '1000 tonf hammer line', etc. Generally, the equipment in a forging line are bought and established together at the same time. During cost estimation, all the equipment costs in the forging line that is used, should be considered. The equipment usage cost may include the depreciation cost, setup cost, operating cost, maintenance and repair costs.

Depreciation is the measure of wearing out, consumption or other loss of value of a fixed asset whether arising from use, obsoloscence through technology

and market changes [1]. Basically, depreciation may be defined as the decrease in value of a physical asset with the passage of time.

The difference between depreciation cost and other overhead costs is that, it is an imaginary item of expense. For cost items like electricity and salaries actual cash flow takes place. However, for depreciation no cash flow occurs, the charge is merely a bookkeeping entry essential for accountants. However, it would be unrealistic not to include the cost of expensive equipment and machines in the cost of a product and depreciation is the most practical way this can be done. Information about depreciation and depreciation accounting methods, are given in Appendix C.

Reflecting depreciation cost to product cost in overhead cost item is a common methodology. Other more realistic method is the calculation of the depreciation cost and directly applying it to the product cost in the equipment usage cost item. In the cost estimation software, both of the methods can be used according to the selection of the user. If the user inputs the required depreciation data to the forging line database, depreciation cost can be calculated and directly reflected to product cost.

Set up cost is the cost for setting up the dies, tools and forging equipment for forging operation. Set up cost is generally reflected to unit forging cost, on time basis considering the set up time [33]. For production batches including greater quantity of forgings, set up cost is smaller per unit forging.

Operating cost includes the costs that should be spent for operating the equipment like electricity, oil and regular spare part costs. For forging industry, main operating cost items are the electricity cost used by the forging equipment and the cost of the wearing parts that should be changed regularly like brakes, ram connection elements.

It is generally hard to calculate the hourly operating costs for forging equipment. Therefore, the common method is to consider the operating costs in overhead cost item. However, if hourly operating cost can be calculated, it should be added directly to the equipment usage cost. The estimation computer program

lets the user input the hourly operating cost in the equipment database and reflect the operating costs directly to production cost.

Repair and maintenance costs include the costs that occur due to repairing and maintenance operations done to repair and hold the forging equipment in service. Repair service cost, cost of the spare parts that should be changed, training costs and the salary of the maintenance personnel, costs of the repairing tools used by the maintenance personnel are examples of repair and maintenance costs. It is hard to calculate the maintenance and repair costs and reflecting these costs directly to product cost is much harder. Therefore, it is a common method to consider maintenance and repair costs in overhead cost item.

The forging equipment is selected, considering [2, 24, 36]:

- required forging force,

- forging shape complexity,

- forging weight,

- forging dimensions,

- forging material type,

- quantity,

Details of those items have been given in Section 2.6. In this study, the cost estimation software calculates the forging pressure, forging force, forging shape complexity and the forging weight. For selecting a suitable press or hammer, it is generally necessary to predict the forging force. For estimating the forging force, Drop Forging Research Association's (DFRA) approach, equations 2.8 and 2.9 are used. Shape complexity is calculated by the equation 2.11.

The cost estimation program includes a database containing the cost, service year, force capacity, maximum forging weight, and dimensional limitations of the forging equipment. The cost estimation software suggests the most appropriate equipment to the user, considering the forging force, forging weight and the dimensions of the forging part. After the user's approval or own selection, the

software calculates the cost of the forging machine usage and add it to the total costs. If the optimum forging line is not available at the moment then the user may select another forging line.

4.5 Forging Die Cost

Forging die cost includes the cost of designing and manufacturing the forging dies and tools used to produce the forging. Forging die cost per forging is the cost of the forging dies and other tools divided by the quantity of the forgings.

According to Hobdel and Thomas, the die costs are about 10 percent of the forging cost as discussed in Section 4.1. For open die forgings, the die costs may be about 1% and for precision forgings where higher tolerances are used, tooling costs may be higher than 10% [24].

The cost of tooling should include the;

- Cost of the die material,

- Designing, solid modeling and NC code generation cost,

- Cost of machining the required geometry (milling, EDM, finishing, etc.),

- Heat treatment cost,

Materials of appropriately high quality are used for the dies and the die material cost constitutes a big amount. Initial unmachined die block weight can be calculated by volumetric calculations, from the material sizes large enough to enable the required tooling to be produced. In estimation software, the user should input the number of required dies, select the die material and input unmachined die block dimensions. The software includes a die material database for the die material cost calculations.

The salary of die designers and the cost of the programs they use, should be reflected to the product cost. General procedure is to consider the die design cost as engineering expenses in the overhead cost item.

The cost of 3D modeling and NC code generation should be added to the product cost. If models and NC codes are generated by CAD/CAM service providers outside the factory, the cost of solid modeling and NC code generation can be obtained per model basis. If the forging company includes a CAD/CAM division, the cost of solid modeling and code generation can be obtained similarly or can be considered as engineering expenses in the overhead cost item.

Cost of machining die material is very high, as machining of hard and tough die steel is hard and too much time is spent on machining. Cost of die machining can be found by multiplying the machining time with the hourly usage cost of the used machines one by one and then summing all of the machine usage costs. The hourly usage cost of a machine is a value that should include the energy expenses, maintenance cost, depreciation cost, cutting tool cost etc. The hourly cost of the operators who operate the machines should also be considered.

Total die machining cost is equal to:

$$C_{tdm} = t_{m1} * (C_{m1} + C_{op1}) + t_{m2} * (C_{m2} + C_{op2}) + \ldots \quad (4.2)$$

Where, 't_m' is machining time, 'C_m' is hourly usage cost of the machine and 'C_{op}' is the hourly operator cost.

The main cost item in the die machining is the use of vertical milling machines. The machining time in vertical milling includes the rough milling time and the finish milling time. Die milling time can be found by using the formula 2.12 - 2.17.

EDM electrodes, which are the negative geometries of the desired machining volume, are generally machined from graphite or copper. Machining of relatively soft electrode material is easier; however, it is a cost item and should be considered. EDM machining cost is not very high, however the expense of electricity and cost of EDM machine usage should be considered in cost estimation. EDM machining time can be estimated from previous work.

If it is required to use other types of machines like lathe, conventional milling machine, shaper and WEDM machine; the cost of use of those equipments should be considered and added to the die machining cost. In the cost estimation software, the user should select the machines and input the machining hours of the used machines. Hourly machine usage cost and operator cost are calculated by using the data obtained from the machine database. Hourly machine usage cost and machining hours are multiplied to find the machine usage cost.

The cost of hand finishing on dies, grinding and polishing, can be calculated by determining the approximate man-hours from similar past work and by experience [30]. In the estimation program, the user should input the required hand finishing hours, and then by multiplying the hourly hand finishing labor cost with the hand finishing hour, the die hand finishing cost can be found.

Die heat treatment costs can be calculated considering the weight of the die material. Heat treatment is generally done in the specialized firms and cost is paid according to the type of heat treatment process and the weight of the die material.

$$C_{dht} = Q_{die} * C_{kgdht} \tag{4.3}$$

Where, 'C_{dht}' is die heat treatment cost, 'Q_{die}' is die weight and 'C_{kgdht}' is the heat treatment cost per one kgf of die material.

4.6 Labor Cost

Labor cost comprises one of the most important cost items of a manufacturing operation. Labor estimation and analysis is concerned with direct and indirect labor.

Indirect labor cost is the cost of the personnel who are necessary for production, but who do not work directly on the manufactured product. Examples are the wages of security personnel, administrative staff, office personnel, maintenance crew, quality control personnel, cleaners, material handling

personnel etc. The general procedure for charging the indirect labor expenses to production is accepting the indirect labor costs as overhead costs.

Direct labor cost is the cost of the personnel who works directly on the product to convert raw materials into finished goods. For the forging industry, the direct labor are the personnel who works in the forging line on the presses, hammers, heating furnaces and cutting equipment during the forging process.

Accounting for labor costs includes three phases: keeping track of working time, recording and computing earnings and charging costs to production [6]. The timekeeping process is facilitated by the use of time cards and time tickets. After workers earnings are computed through various timekeeping and recording operations, they are analyzed for further cost processing. Data obtained by analysis are the basis for charging labor costs to specific jobs. First and second steps are the duties of the accounting staff. After the analysis stage, one hour direct labor cost or *hourly direct labor cost* is obtained. The cost estimator should use hourly direct labor cost, for charging labor cost to the product cost.

Some idle time during manufacturing should occur because it is impossible to convert all direct labor hours into productive time [43]. Tea breaks, machine breakdowns, minor accidents and material shortages are some common sources of idle time. Generally the idle time is not absorbed as direct labor cost; instead idle time is recorded as the factory overhead. Overtime premiums or pays are recorded as factory overhead costs. In forging industry, generally heating furnaces are the main sources of idle time [2].

The rates used to price labor hours should be adjusted to include paid leave hours such as sick leave, vacations, holidays, etc. There are total of 5 x 52=260 days and 260 x 8 = 2080 hours paid during a normal full year. However, paid leave hours reduce the productive year for estimation purposes down to 1800 hours. Hourly labor rates are adjusted so that 1800 hours estimated will be priced at a full year of salary.

The formula to calculate the labor cost is [3]:

$$C_{lab} = t_f * C_{hlab} * N_{lab} \qquad\qquad (4.4)$$

Where, 'C_{lab}' is the labor cost, 't_f' is the average forging time, 'C_{hlab}' is the hourly direct labor cost and 'N_{lab}' is the quantity of the direct workers.

For forging, industry the general procedure starts with computing or assuming the manufacturing time per a forging product. The manufacturing time in the forging line includes; time for cropping the billets, time for heating, preforming, forging and trimming operations. Once the time spent in the forging line is estimated, the forging line workers cost should be charged to forging product. The number of the workers in the forging line is multiplied with the forging time and this value is also multiplied with the direct labor cost per time.

In cost estimation, there are three time sources for time estimates:

- Guesstimate

- Historical records

- Tabulated data (from time studies, man-hour reports, work sampling)

In this study, three methods are used to obtain the forging time spent in the forging line. The first method is, directly inputting the forging time spent in the forging line from the past experience and data. The second method is inputting the approximate kilograms of forging material that can be produced per shift. The third method is inputting the quantity of the forgings that can be produced per shift. The second and third methods also depend on past experience and data, however as these data include idle time, forging time obtained with these method are more conservative and reliable.

4.7 Overhead Cost

Factory overhead consists of all the manufacturing costs, which cannot be associated with the products and must be prorated among all the cost units on some arbitrary basis [3]. Factory overhead is generally divided into three categories as; indirect materials, indirect labor and other manufacturing overhead.

Factory overhead includes:

- Indirect material costs like; shop supplies, office supplies, lubricants, vehicle gasoline, cleaning compounds, small tools, etc.

- Indirect labor costs like; production supervisors and managers, quality control personnel, office personnel, maintenance crew, plant security personnel, material handling personnel, cleaners, cook, drivers, etc.

- Other manufacturing overhead costs like; repairs and maintenance of the factory machinery, equipment and building; insurance expenses on the factory machinery, equipment and building; heating and lighting in the factory, office expenses, factory rent, property taxes, depreciation of the factory building, machinery and equipment, research and development, accounting, engineering, etc.

The factory overhead can be divided into two sub classifications as fixed factory overhead and variable factory overhead [10]. Fixed overhead costs are standard costs that do not vary in amount from a period by period or with respect to changes in the output, whereas variable overhead costs may deviate in amount with the time or changes in the output. Examples for fixed overhead costs are factory rent, insurance, property taxes and examples for variable overhead costs are the repair costs, indirect materials, power and lightning.

As plants have become more automated, the factory overhead costs have increased as a percentage of total manufacturing costs [43]. All production costs other than direct costs, which can be classified as overhead costs, are generally summed up in an *overhead cost pool* as total factory overhead cost [2, 9]. Then the factory overhead cost should be associated and applied to production cost.

To meet its own needs, each company designs its own cost accounting system to classify and accumulate, factory overhead costs to a product cost. As it is stated above, some of the factory overhead costs occur on a regular basis like indirect labor cost and rent. However, many of the factory overhead costs are not regular type, which will not be known until the end of the accounting period. For example, repair costs tend to be heavy in some periods and light in other periods,

also factory-heating costs are incurred only in the cold months [6]. This inconsistent occurrence of overhead costs present a problem for cost estimation, as cost estimation cannot wait until the end of an accounting period to determine the amount of the overhead that should be charged to production. In order to overcome the shortcomings of charging overhead costs to production, factory overhead costs are assigned to production by using a predetermined 'factory overhead rate'.

To obtain the factory overhead rate, the factory overhead must be related to an 'activity base'. The activity base should be directly related to the actual occurrence of the overhead in the firm, in other words the activity base should act as a 'cost driver'. Cost driver is an activity, which causes the overhead to occur. General cost drivers in a manufacturing factory are the direct labor hours, direct labor cost, machine hours, units of production and direct material cost. The activity base chosen should be the best possible measure of the cause and effect relationship between the overhead costs and the volume of the production. The activity base should provide realistic results and should be easily applicable. The general relation for calculating the overhead rate is shown below [11].

$$\text{Overhead rate} = \text{total factory overhead costs} / \text{estimated basis level} \quad (4.5)$$

For forging industry, selection of the direct labor hours as an activity base is an appropriate and easy to apply method. The general formula, which is also used in the estimation software, for calculating the overhead rate becomes [3]:

$$R_{dlh} = C_{fo} / t_{fdl} \quad (4.6)$$

where, R_{dlh} : overhead rate on basis of direct labor hours,

   C_{fo} : total factory overhead cost,

   t_{fdl} : budgeted total factory direct labor hours.

For example, if yearly estimated total factory overhead costs for a forging company are $100.000 and yearly estimated total direct labor hours are 50.000

hours then, 100.000 / 50.000 = \$2 factory overhead rate should be applied for each direct labor hour that is spent on a job. Overhead cost per forging can be found by;

$$C_o = R_{dlh} * t_f * N_{lab} \qquad\qquad (4.7)$$

where, R_{dlh} : overhead rate on basis of direct labor hours,

   t_f : average forging time,

   N_{lab} : the quantity of the direct workers in the forging line,

Once the activity base is chosen, selecting a period of time to serve as a basis for computing the factory overhead rate is necessary. Most companies use an annual period, as periods shorter than one year are usually not satisfactory due to the seasonal fluctuations in the manufacturing and overhead expenses. But some firms may prefer a monthly period. Cost estimation software lets the user to select annual or monthly period.

Factory overhead is estimated because it is impossible to trace the overhead costs to a particular job directly. Consequently, the only acceptable way to assign factory overhead costs to production is through estimate.

4.8 Billet Heating Cost

The forging billets are heated up to very high temperatures, generally between 1200^0 C - $1300\ ^0$C and therefore, high heating expenses occur. Heating cost is stated to be about 4% of the forging costs [25].

Heating equipments are included in the forging lines and generally established together with the other equipments in the forging line. So that the heating equipment depreciation cost may be included in the forging line depreciation cost.

The electric consumption of the induction heaters and the gas or oil consumption of the furnaces should be included in the product cost. The heating expenses may vary from plant to plant. Therefore, generally, experimental results are used in each plant, and each company uses its own heating cost data [2]. Heating cost per unit weight of the forging material for induction, oil and gasoline furnaces should be obtained experimentally from the past data.

According to the forging line that is used and the furnace type, the cost of billet heating can be formulated as.

$$C_{hf} = C_{hkg} * Q \qquad\qquad (4.8)$$

Where, 'C_{hf}' is the heating cost per forging, 'C_{hkg}' is the heating cost per kgf of the forging material and 'Q' is the weight of the forging in kgf.

4.9 Secondary Operations Cost

Secondary operations cost like pickling, tumbling, cleaning, sandblasting, shot peening, heat treatment, coating and painting, which are explained in Section 2.9, should be considered in the forging cost estimation.

Secondary operations costs can be based on forging weights and an estimate of cost can be obtained considering the forging weight [30]. In this study, the forging weight is taken as a basis for reflecting the secondary operations cost to product cost. Weight of the forging is multiplied with the secondary operation cost per weight of the forging. Secondary operations cost per weight of the forging should be calculated and experimentally analyzed by forging companies. Heat treatment, coating and painting processes are generally done in specialized firms as explained in Section 2.9. Heat treatment, coating and painting costs are calculated considering the type of the heat treatment operation, type of coating and painting material and the weight of the forging. Cost estimation software uses the same methodology based on the forging weight.

4.10 Quality Control Cost

In forging industry, quality control is very important as explained in Section 2.8. Allocation of quality control costs directly to product costs is a problem. The general tendency is to consider the quality control costs in the overhead cost item. The quality control engineers, technicians and workers are indirect workers and the small equipments they use like vernier callipers, micrometers are also indirect materials, which can be grouped in the overhead cost item. The quality control office expenses can also be considered as overhead costs. The cost of establishing and maintaining a quality control and metrology laboratory can be allocated to product cost by using depreciation cost of the construction and the equipments in overhead cost group.

The forging operators are an important part of the quality system, a well-trained experienced forging operator can detect many of the defects that are visible to eye and alert the proper quality control personnel. The wages of the forging operators are considered in the direct labor cost group so the cost of using forging operators and workers who cuts the billets are not required to be reflected to the quality control cost item.

Non-destructive testing, which is introduced in Section 2.8, is a prominent cost item, and excessive testing will result in uncompetitive pricing. Inspection costs may reach to 10% percent of production costs for some forgings [24]. For the cases of non-destructive testing applications, if the application cost of expensive methods like magnetic particle and ultrasonic testing are considered as overhead costs than other simpler products costs, which do not require expensive tests will increase and the compatibility of the company will decrease with the high prices given to customers. Therefore, if special quality control and testing methods are required for some forgings, the cost of these tests should be reflected to only these products. For small shops, which use the service of independent testing laboratories rather than purchasing expensive testing equipment, the cost of the tests should not be considered in overhead cost item and should be reflected to product cost directly.

In cost estimation software, quality control costs are considered to be in overhead cost item. If the user wants to consider special tests and special process controls, the quality control costs can be calculated and added to product cost per unit basis.

4.11 Shipment Cost

Shipment cost details are explained in Section 2.10. Package cost may be added directly to the product cost per unit base. If special packaging and packaging requirements are necessary for special forgings, requirements should be described by the customer at the contract, and the cost estimator should consider additional packaging cost.

The required quantity of the transportation containers, to carry all the forgings to the customer should be calculated considering the container carriage capacities and then the quantity of the containers should be multiplied by the unit container cost and added to transportation cost.

The cost estimator should acquire transportation cost from the transportation firms by giving the details of transportation, incoterms, destination place, type of the load, total weight, transportation container quantity etc.

The cost estimation software calculates the quantity of the transportation containers, weight of the filled containers and the total weight to be transported and helps the user to obtain transportation cost from the transportation firms. After the user inputs the transportation cost, total shipment and per unit base shipment cost is calculated and added to forging cost.

CHAPTER 5

OVERALL STRUCTURE OF THE FORGING COST ESTIMATION SOFTWARE

5.1 Introduction

At the beginning of this study, some general aims and desired specifications of the cost estimation software have been determined. Those general aims can be listed as follows. The cost estimation software should;

- perform the cost estimation process for hot forging products providing fast and to some extent accurate results.

- be user friendly and easy to use and contain a user help module.

- include a clean and simple user interface that follows standard Windows software conventions.

- be free from errors as possible. The software should deliver clear error messages and should recover from both input errors and the programming errors.

- contain databases that store the information necessary to prepare an estimate, including material, machinery, equipment and other cost item prices.

- contain a standard file system for backing up the estimates. The software should permit the user to export the results into a file format that can be read by the estimation software, so the user can revise the estimates.

- give printable results for documentation aids.

5.2 Structure of the Forging Cost Estimation Software

The cost estimation software, available in the market may not always exactly fit the general requirements or work patterns of the user. Therefore, firms may prefer to develop their own cost estimation software. While a computer software is being developed, the software developer generally has no knowledge about the process, logic and the methodology. A way of communication between the user and the software developer is required. While this cost estimation software has been developed, as the software developer was informed about the forging process and the estimation methodology, the software development period has been shortened.

In this study, Microsoft Visual Basic 6.0 is selected for developing the estimation software. By using a visual language, it would be easier to prepare a user interface similar to Windows environment. Visual Basic program includes date aware elements, which allow the software to access and manipulate the data stored in databases created with database programs. By the written program code, the graphical menus, buttons and data input boxes perform the required tasks.

The cost estimation software, which has been developed in this study, is named as "FORGE COST ESTIMATOR". *Forge Cost Estimator* software includes different modules for calculation of different cost items. The cost items that are calculated by using different modules of the software are summed up in an additive structure by using bottom-up cost estimation method as explained in Chapter 4. General flow diagram of the *Forge Cost Estimator* is shown in Figure 5.1.

About 13000 lines of codes have been written and above 60 forms have been prepared to constitute the *Forge Cost Estimator* software. However, the program code has been tried to be written in a simple and easy to understand logic for future modifications and possible updates.
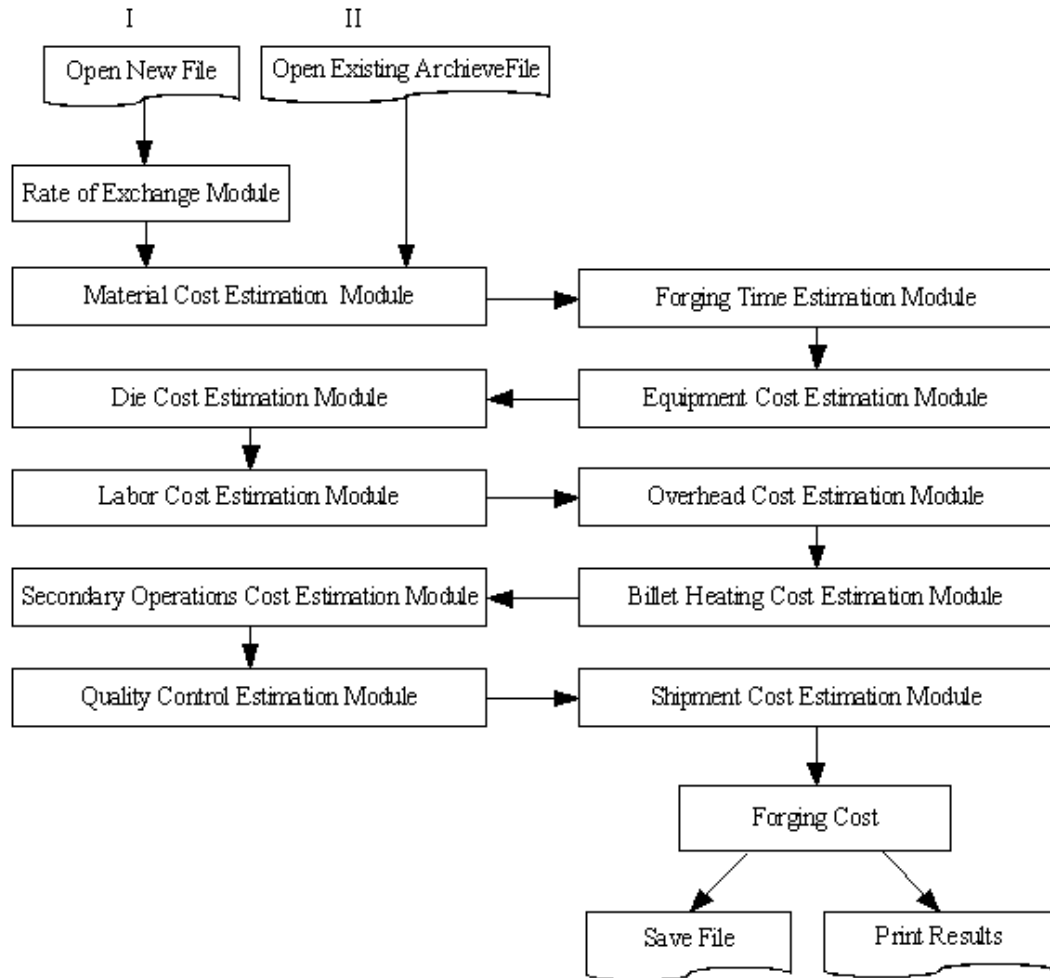
Figure 5.1 - General Flow Diagram of the *Forge Cost Estimator*

The material cost estimation module includes a volume estimation system named as "*Easy-Volume*", which is a new proposed system for calculating the forging volume quicker and easier. *Easy-Volume* has been explained in Chapter 3.

By using the die cost estimation module, cost of the dies can be obtained including the material cost, machining costs and other related costs. Die cost estimation module includes different sub modules for estimating the costs of the die material, design and NC code generation cost, die milling, EDM electrode material, EDM electrode milling, EDM machining, die machining, hand finishing.

The forging equipment cost estimation module, calculates the forging pressure, load and shape complexity; considering the forging weight, load and the dimensional limitations of the forging equipment, suggests to the user the most convenient forging line from the database. In other words, the software guides the user in selecting the suitable forging equipment.

The software has various databases prepared by using MS Access and MS Excel. The forging equipment and machinery databases include forging equipments and machining equipments technical properties and financial data. The material databases include the cost related material properties and some technical properties like the density.

The software has the property of foreign exchange capability for USA Dollar ($), Euro (€) and a third currency unit, which can be defined by the user. In real life, different currency units may be used for different cost items e.g. heat treatment cost may be defined with Euro and the labor cost may be defined by the local currency unit. *Forge Cost Estimator software* enables the user to work with different currency units in different cost modules.

While, *Forge Cost Estimator* software is being developed; the aims introduced in previous section are always considered. Controls and checks are done by real life applications in forging industry.

5.3 Data for Cost Estimation

In most cases, some cost data are required for the cost estimation. The cost estimate is based on the standards, either company specific or industry wide. Sources of data are;

- Accounting records
- Other sources within the firm
- Sources outside the firm

Preparing cost estimates normally require the use of historical data on manufacturing costs. Historical cost data will be useful for cost estimation only if they are collected and organized in a way that is compatible with future applications. There will be fluctuations in the values of the cost data; therefore the time periods should be short enough to avoid the averaging of fluctuations in production within a period [10]. However, time periods should also be long enough to let the accountants do the recording procedures. Monthly basis cost data seems convenient for many industries. Organizations, which are engaged in cost estimation continually, should keep a file for their own use. The information must be updated with respect to the changes that will inevitably occur. The format of cost data, such as unit costs for various items, should be organized according to the current standard of usage in the organization.

Forge Cost Estimator uses MS Excel for data storage properties. There is a standard file, where the estimation data and company estimation standards or the company cost data are saved. When a new estimation process is started, the company cost data is copied to the new file; by this way the estimation period is shortened. The estimations can be saved on computer or data storage devices and the results can be printed. The software lets the user to revisit the saved estimations and control or modify the estimations.

5.4 Flow Diagrams

Flow diagrams are helpful tools to overview and show the general structure of the software. In this section, *Forge Cost Estimator* logic and structure is tried to be explained by means of flow diagrams. Flow diagrams show the procedure to calculate a cost item and the structure of the *Forge Cost Estimator*'s related estimation modules. Flow diagrams are given within the order of the forging cost estimation procedure and estimation software. In Appendix B, flow diagram shapes and explanations for this study are shown.

In Figure 5.2, flow diagram of the forging material cost estimation procedure is shown. The forging material cost estimation module includes the

Easy-Volume volume estimation system, a sub module for calculating the forge weight, a sub module for calculating the flash weight, a sub module for calculating the waste material weights and a sub module for calculating the material cost by using the forging material and price database.

In *Forge Cost Estimator*, forge volume can be obtained by one of the four ways (I, II, III ,IV), which are explained in Section 3.1. Case 1 occurs, when the 2D technical drawing is sent by the customer and no other information is available for the forge weight. For this case, the *Easy-Volume* volume estimation system is used for the forge volume calculation. Case 2 occurs, when the forge weight is stated by the customer. For this case, the forge weight should be controlled by calculating the forge volume with the *Easy-Volume* system. Case 3 occurs when a 3-D CAD model is sent by the customer. For this case, the forge weight may be found by using CAD software or by using *Easy-Volume* system, as explained in Section 3.1. Case 4 occurs when a sample forging part is sent by the customer. For this case, there is no need to use the *Easy-Volume* system. Forge weight may be obtained by weighing the forging and the forge weight may be input directly to the software.

In the forge weight estimation sub module, the forge weight may be obtained from *Easy-Volume* system or may be input by the user according to the cases described above. To calculate the forge weight, material density may be obtained by selecting the material or may be input by the user. In the flash weight estimation sub module to calculate the flash weight, the periphery of the forging at the parting plane should be input. Flash weight estimation method used in the software is explained in Section 4.3. Waste material sub module estimates the scale loss, tonghold loss, saw-cut and bar-end loss and die wear loss weights by using the methods explained in Section 4.3. For scale loss estimation, the user should select the furnace type.
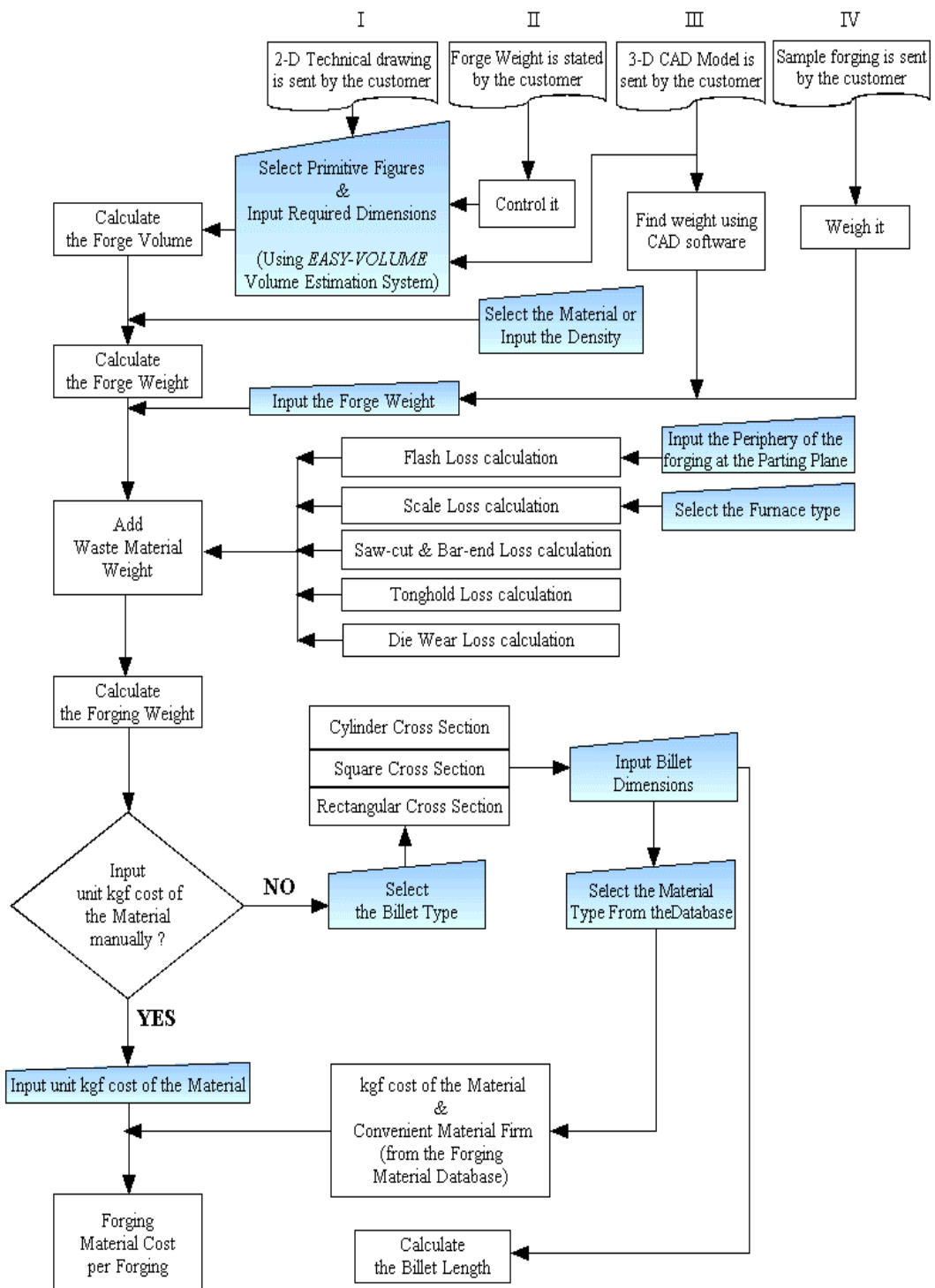
Figure 5.2 - Flow Diagram of the Forging Material Cost Estimation Procedure

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The software adds waste material weight to the forge weight and calculates the forging weight. The forging weight is displayed in the material cost estimation sub module. The user may input unit kgf cost of the forging material manually or unit kgf cost of the forging material may be obtained by the software from the forging material cost database. For the second case, the user should select the billet type, input the billet dimensions and select the material type from the material database. The software will display the billet length, the suitable firm that sells the cheapest material and the unit kgf cost of the forging material. The material database lets the user to input material prices in different currency units for different companies. Finally, forging material cost per forging is calculated.

In Figure 5.3, the forging time estimation module structure is shown. Forging time may be obtained one of the three ways (I, II, III); inputting the approximate weight of the forging material or approximate quantity of the forgings that can be produced per shift or directly inputting the forging time spent in the forging line; as explained in Section 4.6. If the customer wants to consider die and equipment set up cost, which is explained in Section 4.4, total setting up time and quantity of the forgings should be input by the user. Die setting up time per forging is added to the forging time and the average forging time is obtained.

In Figure 5.4, cost estimation procedure for the forging equipment usage is shown. The user selects the forging enveloping shape from the cylinder or prism options and input the dimensions of the selected shape, which is enough to envelope the forging part. Some examples for the enveloping shapes are shown in Figure 2.5. The software calculates the forging shape complexity by using the Equation 2.11. The user should input the cross section area of the forging at the parting plane for calculation of the forging force and pressure by using the Equations 2.8-2.11. The convenient forging line is suggested to the user considering the items explained in Section 4.4, like the forging force, forging dimensions and the forging weight. The forging equipment usage cost estimation module uses a database for obtaining technical properties and financial data of the forging lines. The user may select another forging line or accept the suggested forging line. The hourly operating cost and the depreciation cost is calculated by

the software using the financial data obtained from the forging line database. Forging equipment usage cost per forging is obtained by using the Equation 4.1.
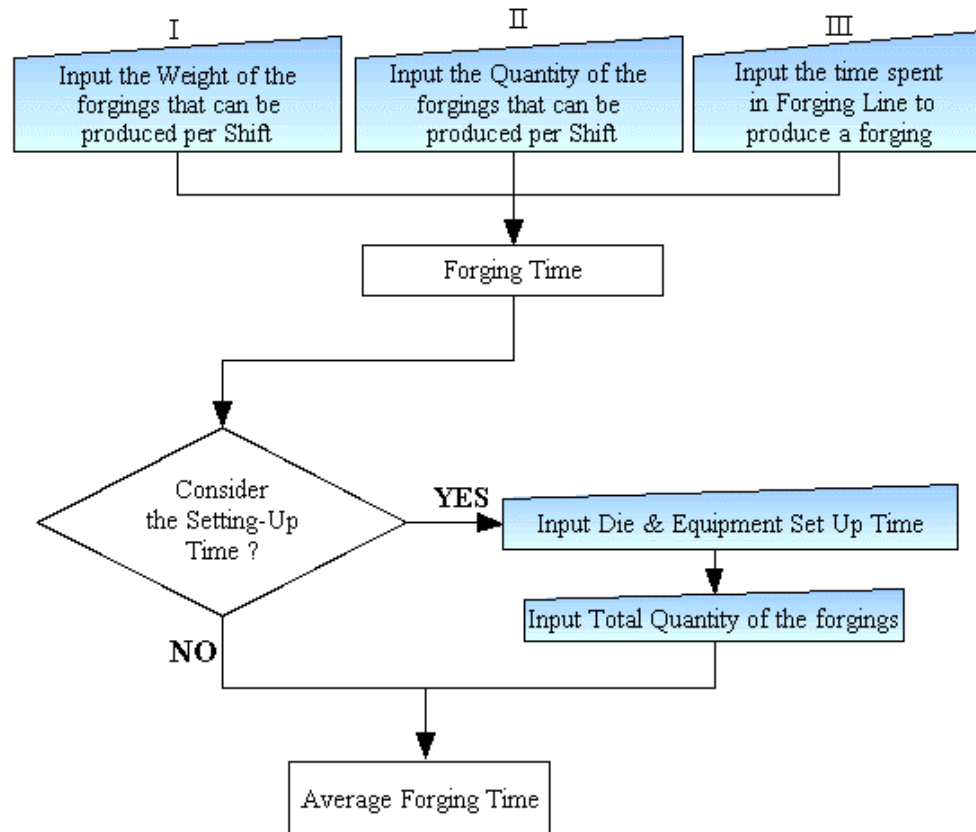
Figure 5.3 - Flow Diagram of the Forging Time Estimation Procedure

In Figures 5.5 - 5.11, the flow diagrams of the estimation procedures of the forging die related cost items are shown. The forging die cost estimation module includes the die material, die milling, EDM electrode material, EDM electrode milling, EDM machining, die machining, hand finishing, design and NC code generation cost estimation sub modules. The forging die cost estimation module uses the milling machine, EDM machine, machines, die material and EDM electrode material databases.
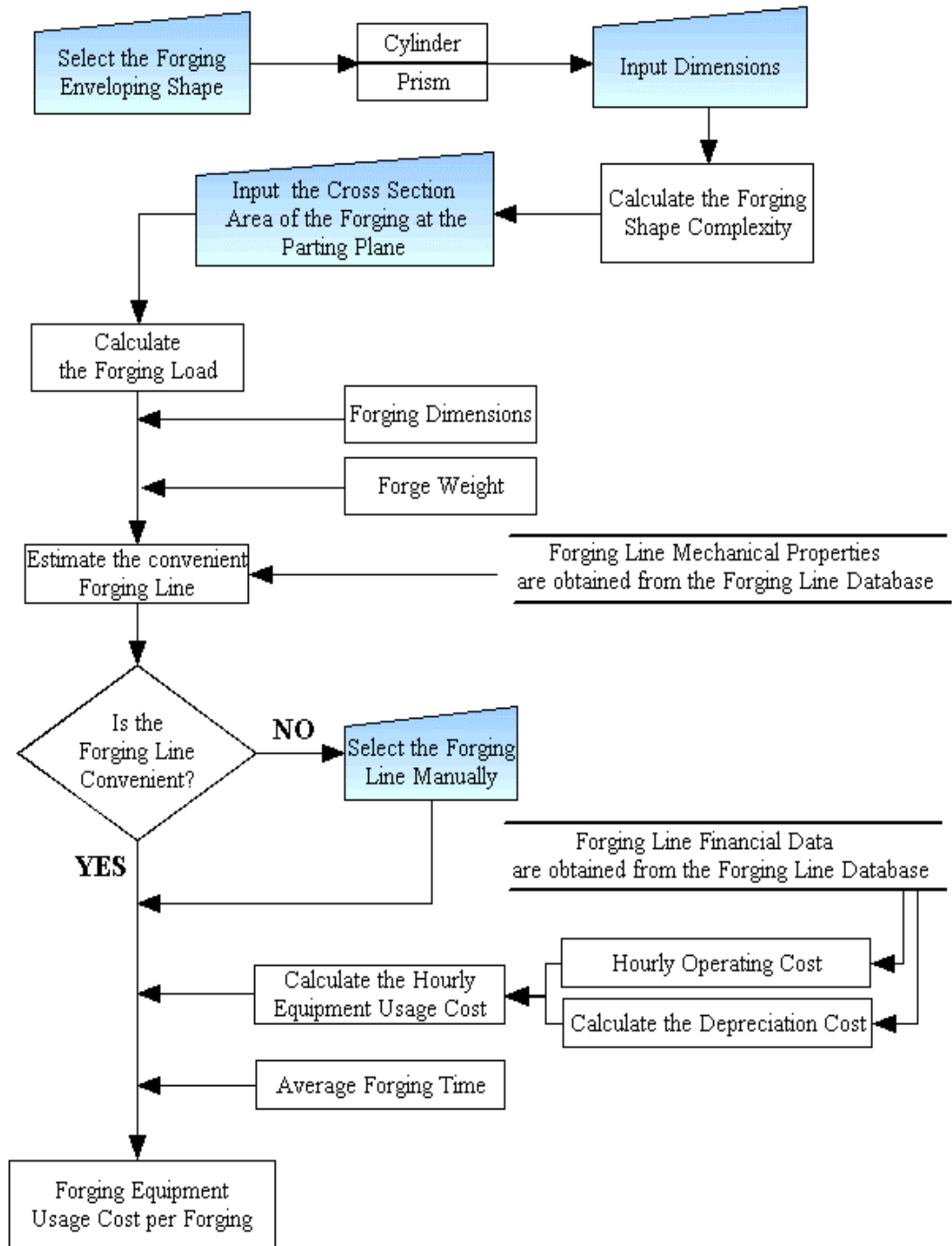
Figure 5.4 - Flow Diagram of the Forging Equipment Usage Cost Estimation Procedure

In Figure 5.5, flow diagram of the die material cost estimation procedure is shown. The user selects the die block shape and input the unmachined die block dimensions, which include both the upper and lower dies. The user should input the required die pairs quantity and select the die material from the die material database. Die material density and unit kgf cost of the die material are obtained by the software from the die material database. Die material volume, weight and die material cost are calculated and displayed on screen.

In Figure 5.6, flow diagram of the cost estimation procedure for die milling is shown. The upper and lower die machining volume is the cavity that will form the forging product, which is in the same shape of the forging product. Therefore, the machining volume is obtained from the forge volume estimation module by the software. The user should input the tool diameter, depth of cut, feed rate and the tool path interval (lateral depth of cut). The rough milling time can be found by using the Equations 2.13 and 2.14 as explained in Section 2.6. If finish mill machining is required than the user should input the forging part surface area, tool diameter, tool path interval and the feed rate. The finish mill machining time can be found by using the Equations 2.15 and 2.16. Total milling time can be found by using the equation 2.17. If special cutting tools are used, extra cutting tool cost may be input by the user for reflecting the tool cost to product cost. The user should select the milling machine for calculating the depreciation cost and obtaining the hourly operator and operating costs from the milling machine database. The die milling cost and operator cost is calculated according to the selected milling machine.

In Figure 5.7 flow diagram of the cost estimation procedure for die EDM electrode material is showed. The estimation logic is similar to the cost estimation procedure for die material, which is explained and shown in Figure 5.5. The die material is replaced with EDM electrode material.
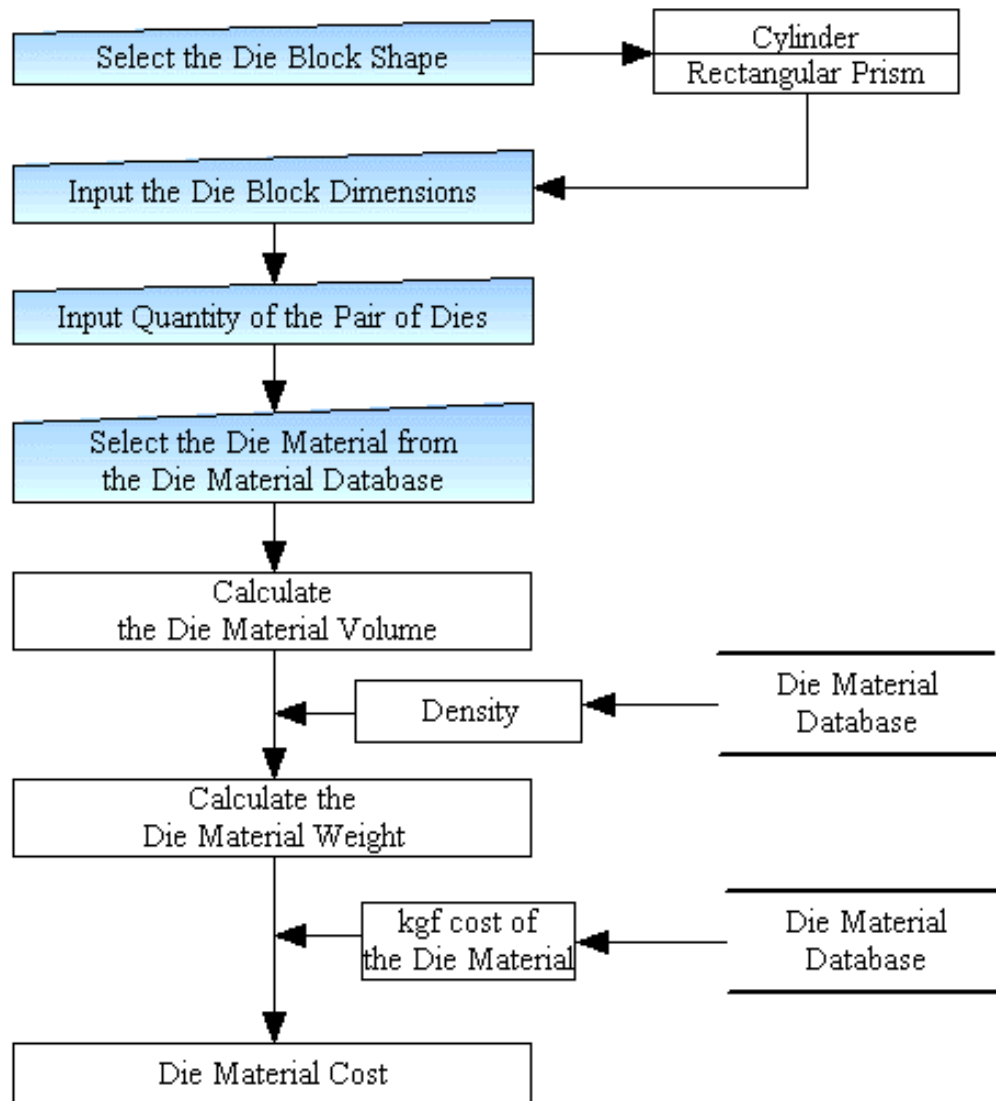
Figure 5.5 - Flow Diagram of the Die Material Cost Estimation Procedure
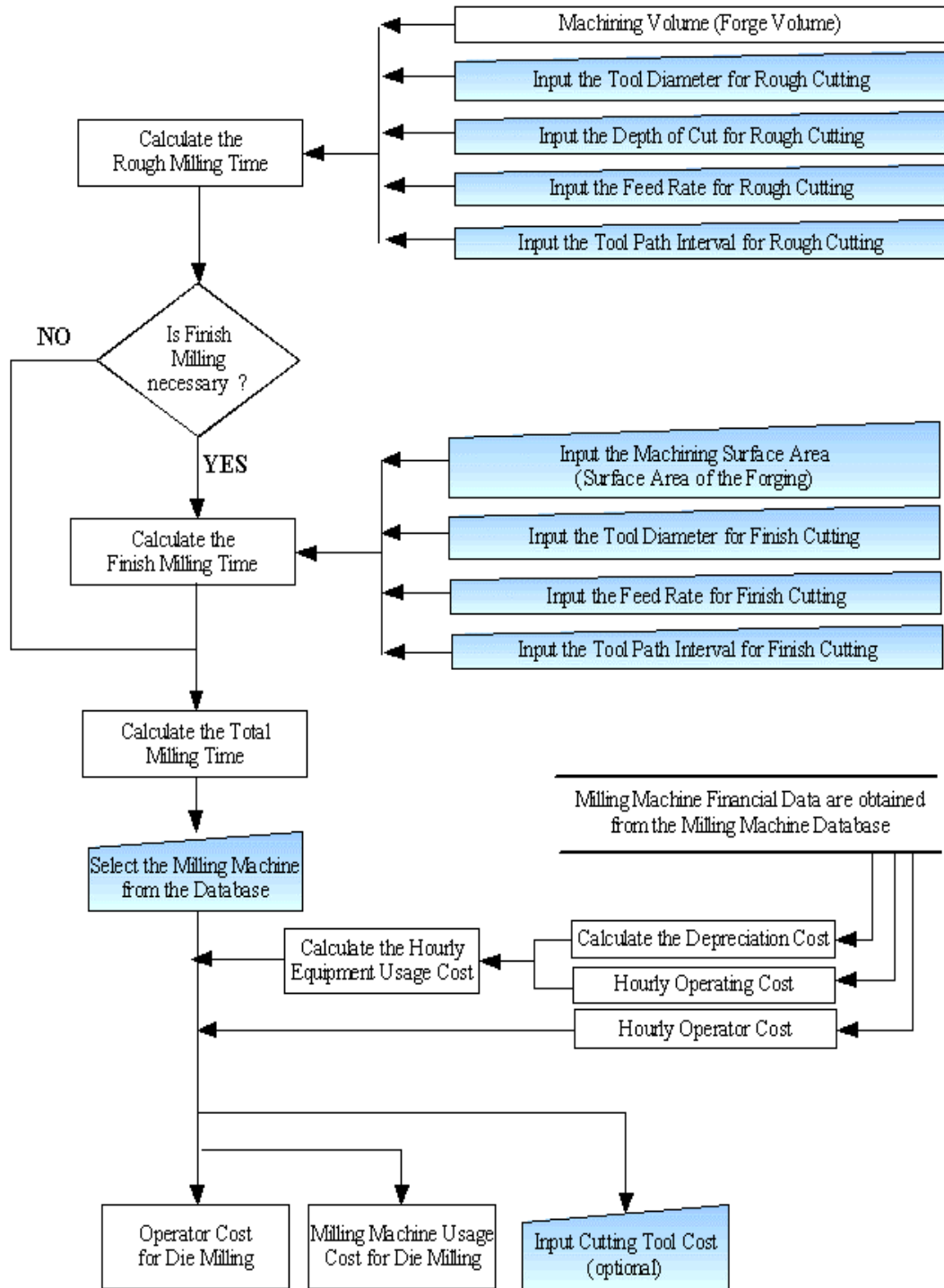
Figure 5.6 - Flow Diagram of the Cost Estimation Procedure for Die Milling
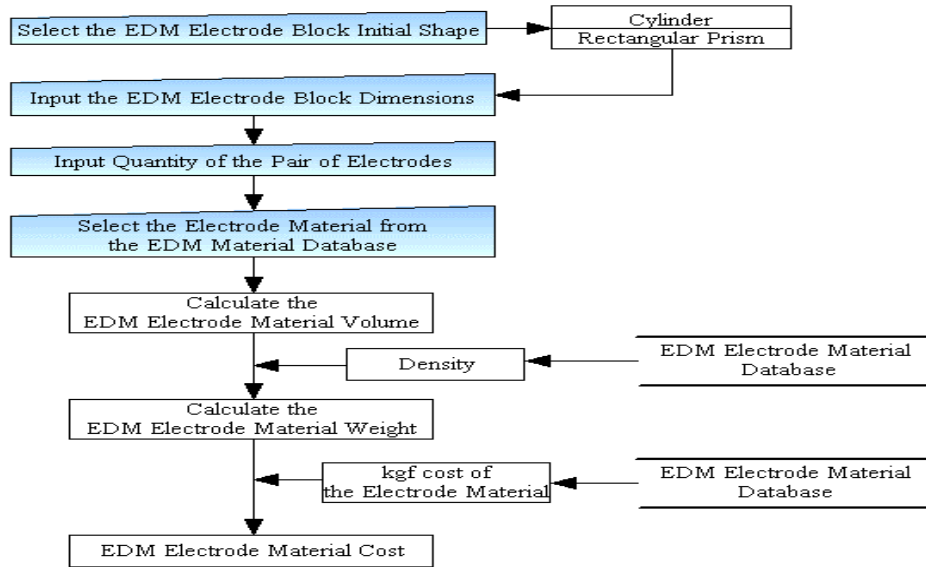
Figure 5.7 - Flow Diagram of Cost Estimation Procedure for Die EDM Electrode Material
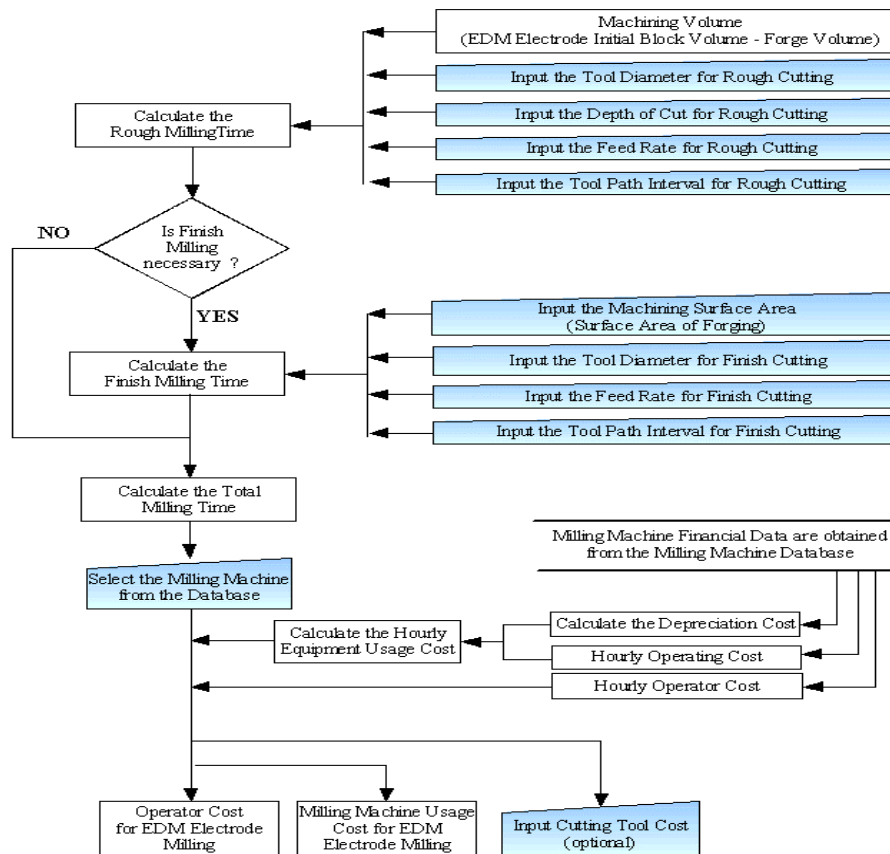
Figure 5.8 - Flow Diagram of the Cost Estimation Procedure for Die EDM Electrode Milling

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In Figure 5.8 flow diagram of the cost estimation procedure for die EDM electrode milling is shown. The estimation logic is similar to the cost estimation procedure for the die milling, which is explained and shown in Figure 5.6. The main difference is in the machining volume. This time, the machining volume becomes the initial volume of the unmachined electrode block minus the forging volume. Machining volume is calculated by the software.

In Figure 5.9 die EDM machining and in Figure 5.10 die machining cost estimation procedure flow diagrams are shown. In both of the sub modules, the user should select the required machine or machines from the database and input the machining time. The financial data of the machines are obtained from the database to calculate the hourly machine usage cost and obtain the hourly operator cost. Hourly machine usage cost may include the depreciation cost and hourly operating cost. The machining costs and the operator costs are the outputs.
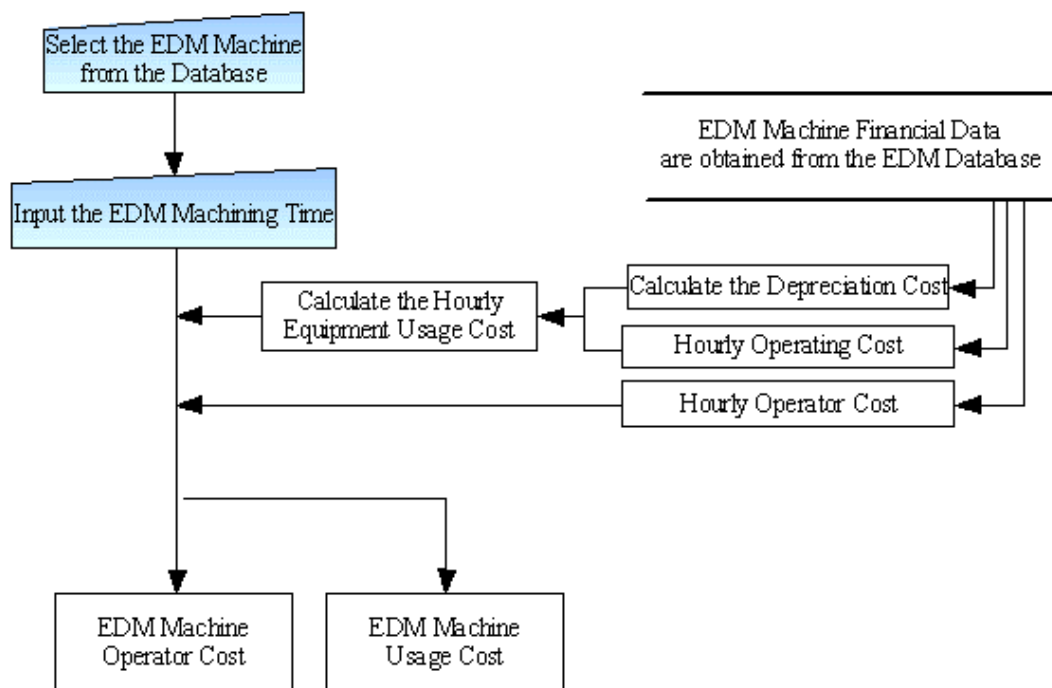
Figure 5.9 - Flow Diagram of the Cost Estimation Procedure for Die EDM Machining
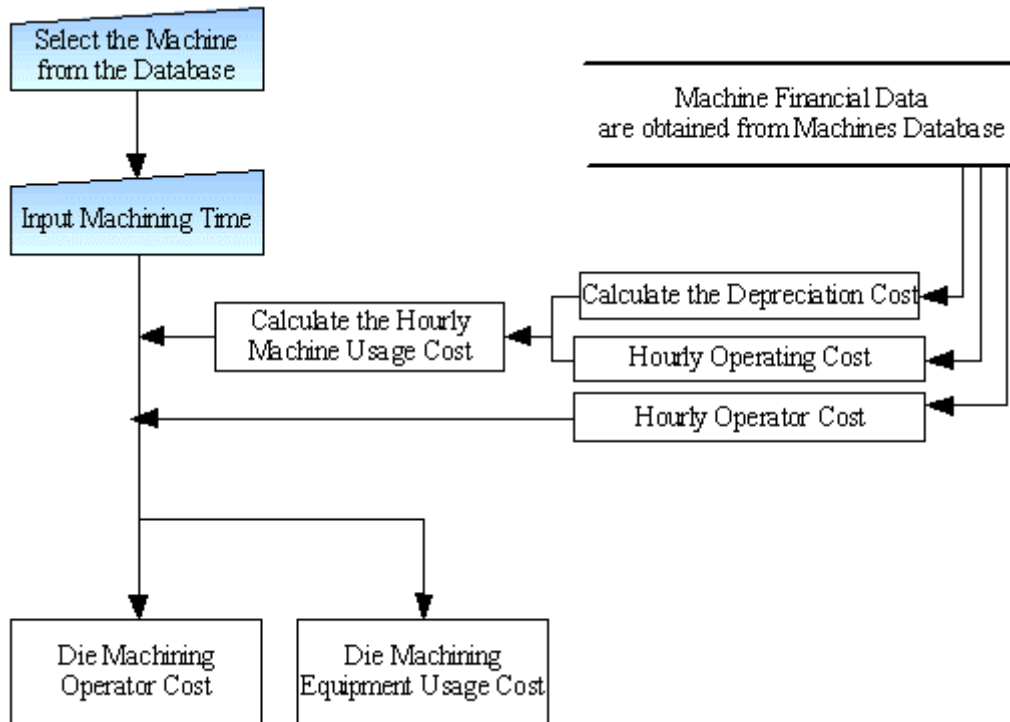
Figure 5.10 - Flow Diagram of the Cost Estimation Procedure for Die Machining
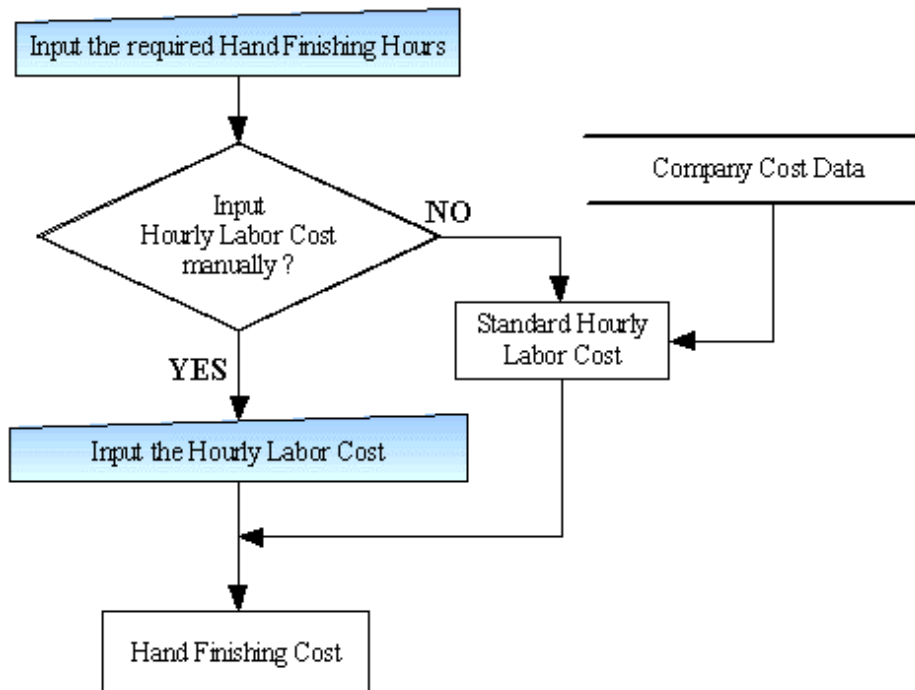
Figure 5.11 - Flow Diagram of the Cost Estimation Procedure for Die Hand Finishing

In Figure 5.11, flow diagram of the cost estimation procedure for die hand finishing is shown. The user should input the required hand finishing hours. The hourly labor cost may be input by the user or can be obtained by the software from the company cost data. Afterwards, die hand finishing cost is calculated.

In Figure 5.12, the flow diagram of the direct labor cost estimation procedure is shown. The direct labor quantity is obtained from the forging line database according to the selected forging line in the forging equipment usage cost estimation module. If required, the quantity of the labor may be increased or decreased by the user for the partial forging process. The standard hourly labor cost is obtained by the software from the company cost data. The average forging time is obtained from the time estimation module by the software. Direct labor cost per forging is the output, which is calculated by the Equation 4.4.
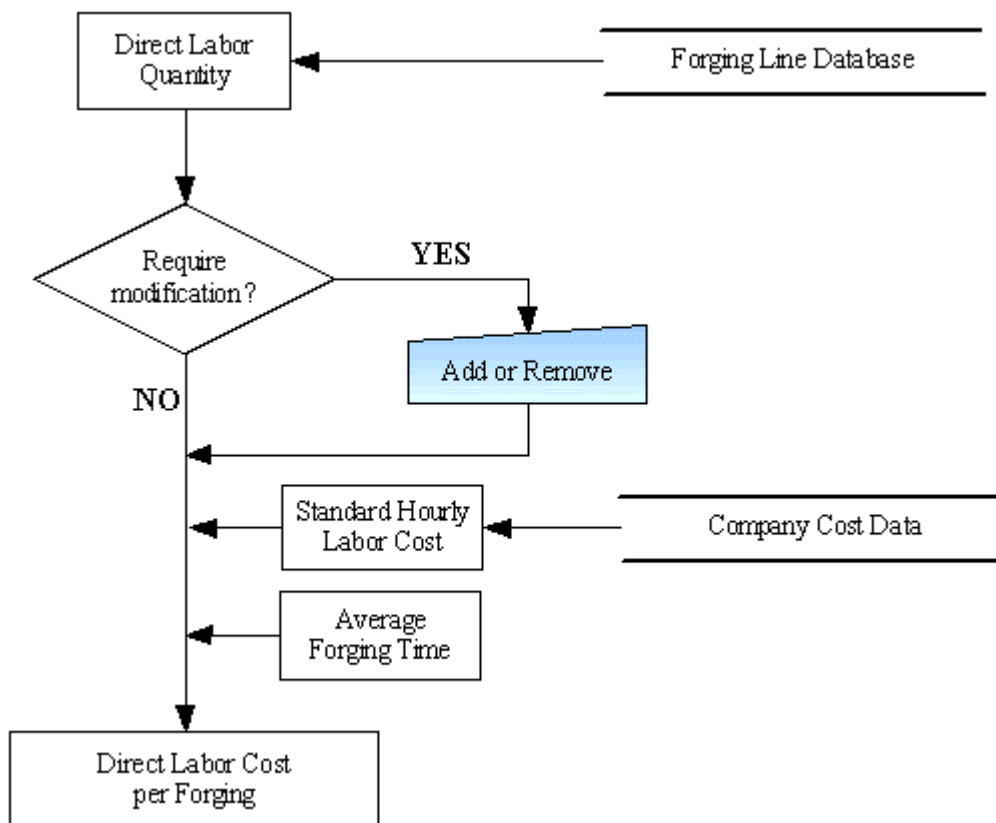
Figure 5.12 - Flow Diagram of the Direct Labor Cost Estimation Procedure
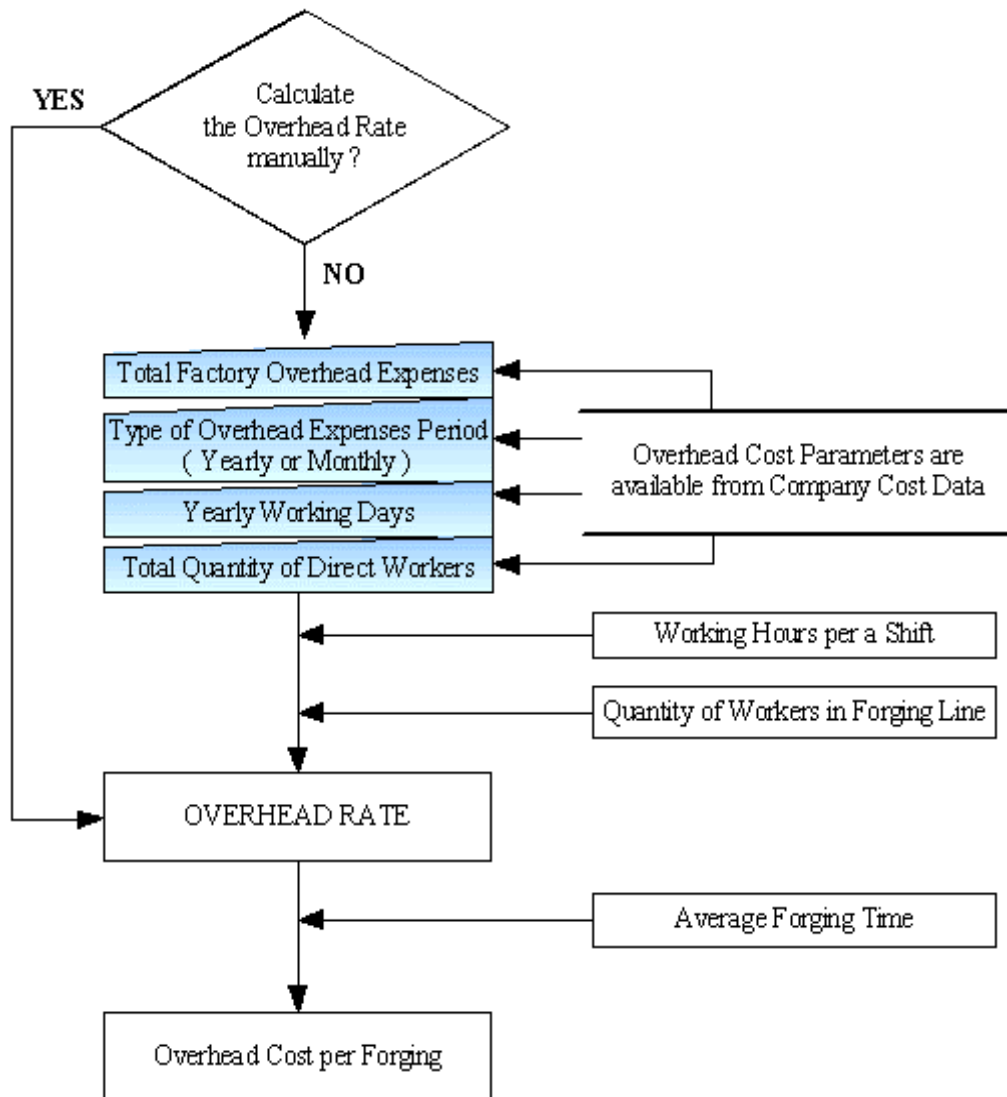
Figure 5.13 - Flow Diagram of the Overhead Cost Estimation Procedure

In Figure 5.13, flow diagram of the overhead cost estimation procedure is shown. The overhead cost estimation module obtains the required overhead cost parameters like the factory overhead expenses, overhead expenses period, etc. from the company cost data and calculates the hourly overhead rate by using the Equation 4.6, which is explained in Section 4.7. The user may change the overhead parameters, if required. The average forging time is obtained from the

time estimation module by the software. The direct labor quantity is obtained from the forging line database according to the selected forging line. The working hours per shift is obtained from the time estimation module. Overhead cost per forging is calculated and displayed.

In Figure 5.14, flow diagram of the billet heating cost estimation procedure is shown. The heating cost estimation module obtains the furnace type from the forging line database according to the selected forging line in the forging equipment usage cost estimation module. According to the selected forging line, the billet heating cost per kgf weight of the forging material is obtained from the company cost data. Forging billet-heating cost per forging is calculated by using the Equation 4.8.
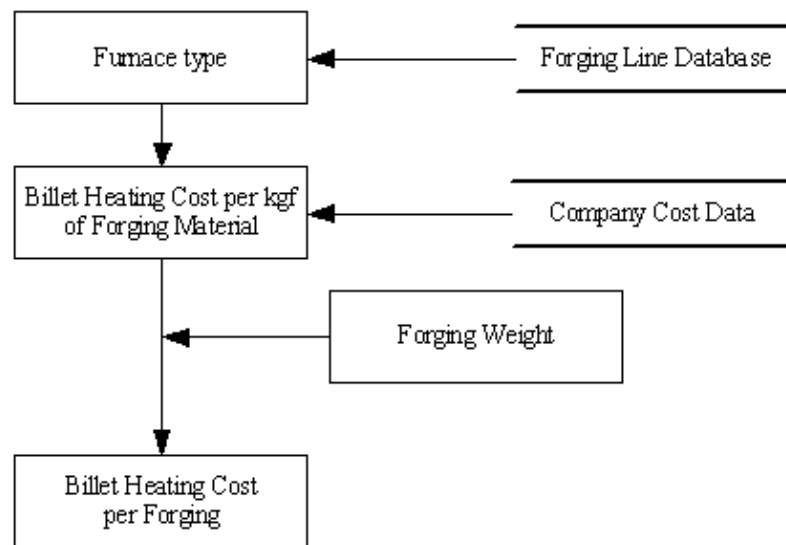
Figure 5.14 - Flow Diagram of the Billet Heating Cost Estimation Procedure
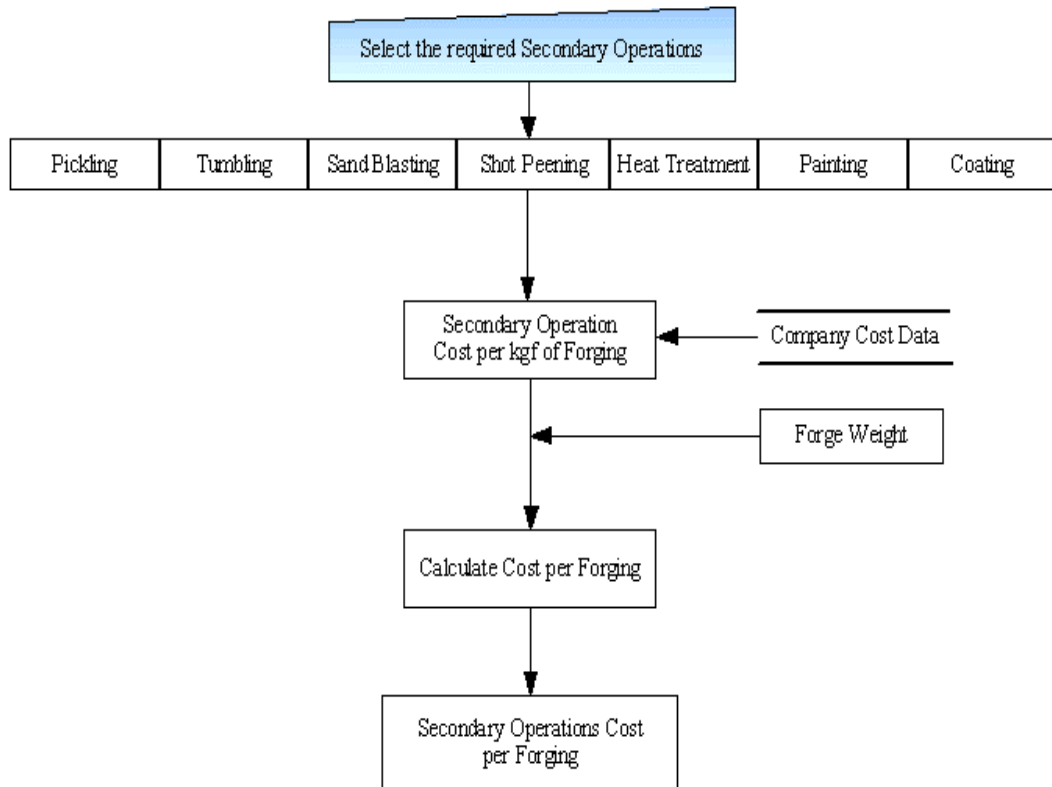
Figure 5.15 - Flow Diagram of the Secondary Operations Cost Estimation Procedure

In Figure 5.15, flow diagram of the secondary operations cost estimation procedure is shown. The user should select the required secondary operation type or types from the operations of pickling, tumbling, sand blasting, shot peening, painting and coating, which are explained in Section 2.9. The secondary operations cost estimation module obtains the secondary operation cost per kgf weight of the forging material for the required operation from the company cost data. Each of the secondary operation cost per forging and the total secondary operations cost per forging is calculated as explained in Section 4.9.

In Figure 5.16, flow diagram of the shipment cost estimation procedure is shown. This module calculates the required quantity of the containers and the total weight to be transported and helps the user to obtain the transportation cost from transportation firms. The method applied is explained in Section 4.9.
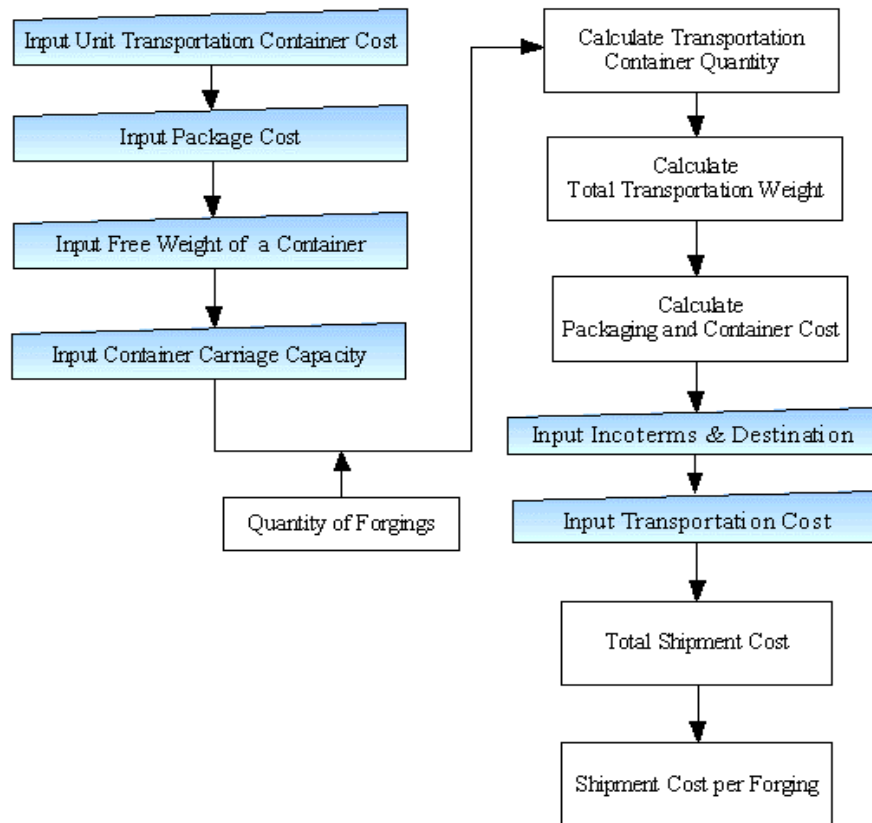
Figure 5.16 - Flow Diagram of the Shipment Cost Estimation Procedure

CHAPTER 6

FORGING COST ESTIMATION SOFTWARE:
"FORGE COST ESTIMATOR"

6.1 Introduction

In Chapter 5, the overall structure of the forging cost estimation software, "*Forge Cost Estimator*" has been explained with the help of flow diagrams. In this Chapter, the *Forge Cost Estimator* software will be presented. Several test runs of the software have been realized by the author and the cost estimator of Aksan Forging Company. One of the test runs is given as a sample cost estimation process to explain the functioning of the *Forge Cost Estimator*. Information about Aksan Company is given in Appendix A.

The sample forging part is shown in Figure 6.1 and the technical drawing of the sample forging is shown in Figure 6.2. Forging material is C45 steel. The forge weight is known as 6950 gf, so that the forge weight can be directly input to the software, without using *Easy-Volume* system.

Figure 6.1 - Sample Forging
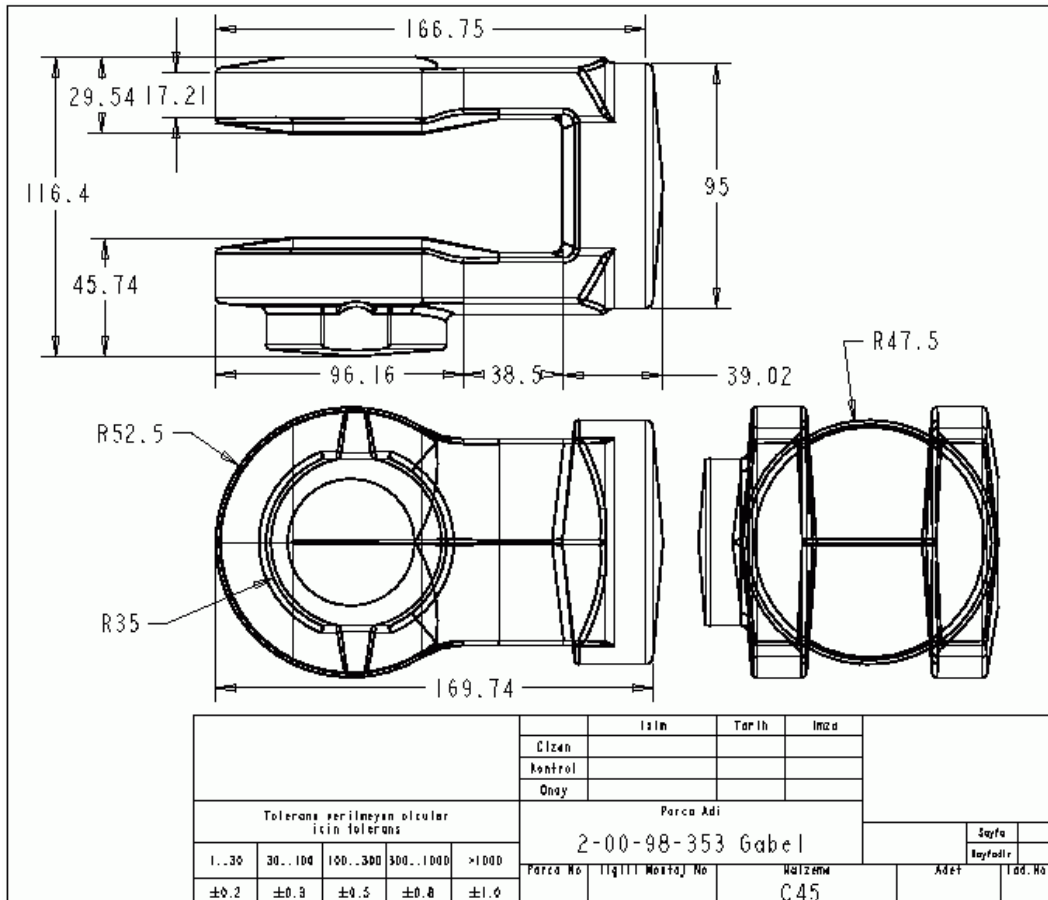
Figure 6.2 - Technical drawing of the Sample Forging

6.2 Sample Run With "Forge Cost Estimator"

When the *Forge Cost Estimator* software is opened, the starting home page of the software comes to the screen as shown in Figure 6.3. There are various user-friendly menus in *Forge Cost Estimator.* Some most often used menus are placed in pictured shortcut buttons for quick availability as shown in Figure 6.4. Each menu group is related with a forging cost item like material, labor etc. and each menu include buttons for opening the sub modules of the related forging cost item. The menus and the modules of the software will be introduced step by step, following the logical cost estimation sequence. In the software, there are *Next, Home* and *Back* buttons in all of the sub modules, which let the user follow the

logical estimation sequence. The user may also open any sub module at any time disregarding the logical estimation sequence.
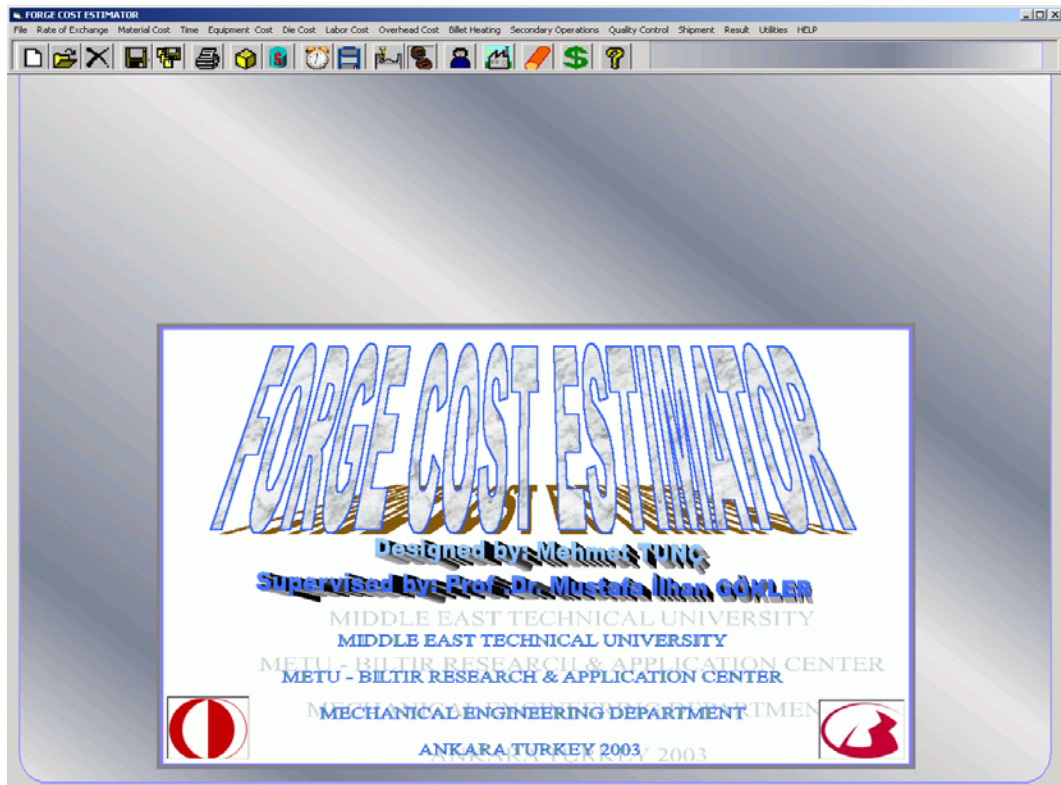
Figure 6.3 - Starting Home Page of the *Forge Cost Estimator*
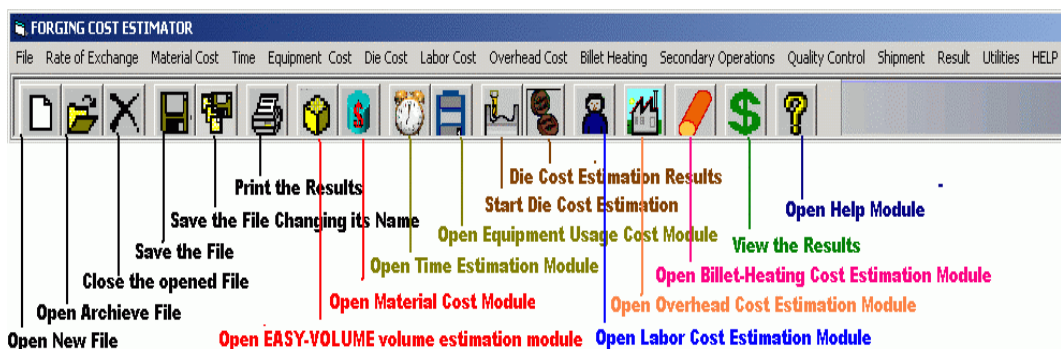
Figure 6.4 - *Forge Cost Estimator* Menus and Shortcut Menus
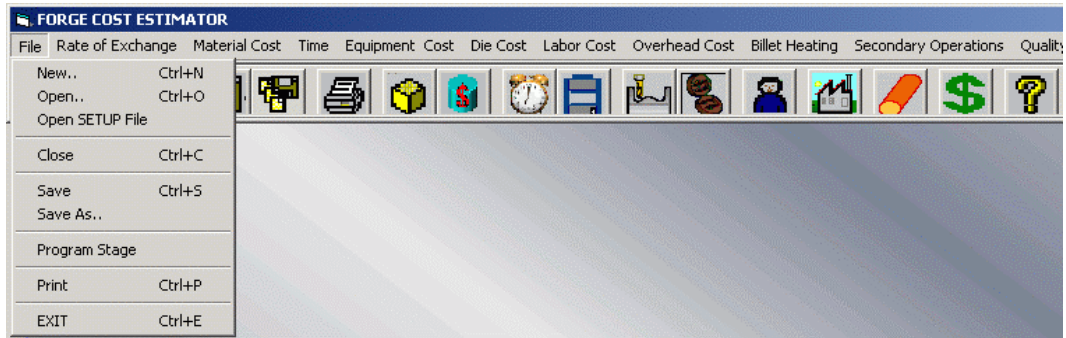
Figure 6.5 - *Forge Cost Estimator* **File Menu**

File Menu is similar to all Windows based software, the menu includes;

New button for opening the new *Forge Cost Estimator* files,

Open button for opening the saved *Forge Cost Estimator* files,

Open SETUP File button for opening and modifying the *Forge Cost Estimator* Set-Up File and the company cost data.

Close button for closing the opened *Forge Cost Estimator* file,

Save button for saving the *Forge Cost Estimator* file,

Save As button for saving a *Forge Cost Estimator* file changing its name,

Program Stage button for letting the user to learn, which estimation modules are completed and continue the estimation process after interruptions like phone calls etc.,

Print button for previewing and printing the results,

Exit button for exiting from the *Forge Cost Estimator*.

To start a new cost estimation process, *New* button should be selected, and a convenient file name should be entered to open a *Forge Cost Estimator* file as shown in Figure 6.6. *Open* button opens a previously saved *Forge Cost Estimator* file from the archive.
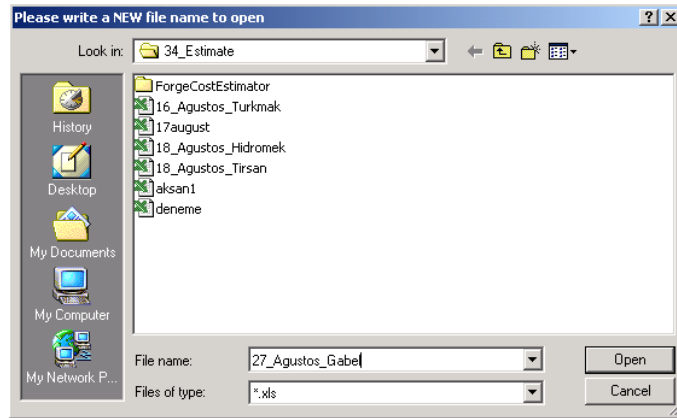
Figure 6.6 - New Button for opening a New *Forge Cost Estimator* File

When a new file is opened, the *Rate of Exchange* sub module becomes active as mentioned in general flow diagram, Figure 5.1. The *rate of exchange* sub module shown in Figure 6.8 lets the user to select the currency unit type, input the currency rate of exchange values and the date. By using the *WEB Connection* button, the currency exchange rates can be obtained from an internet site defined in r*ate of exchange set-up* sub module. If *Set Up* button on *rate of exchange* sub module or button with the same name from the menus is used; the *rate of exchange set-up* sub module shown in Figure 6.9 will appear. By using this module, 3rd currency unit properties like name, symbol and numerical format may be changed. The software has the property of foreign exchange capability for US Dollar ($), Euro (€) and a third currency unit, which can be defined by the user. *Forge Cost Estimator* enables the user to work with different currency units in different cost modules.

Figure 6.7 - The Rate of Exchange Sub Module

Figure 6.8 - The Rate of Exchange Set Up Sub Module
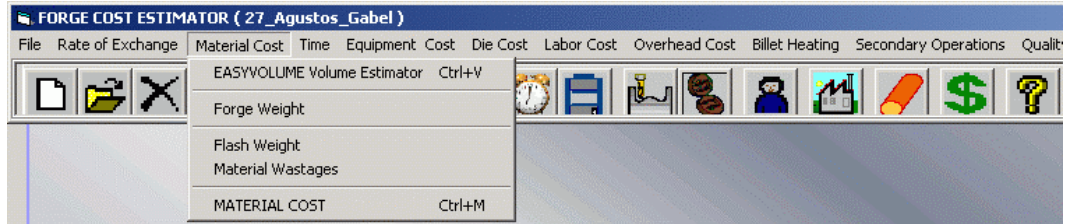
Figure 6.9 - Material Cost Menu of the *Forge Cost Estimator*

Material Cost Menu, which is shown in Figure 6.9, includes the buttons required to open the sub modules related with the material cost estimations:

EASY-VOLUME Volume Estimator button opens the *Easy-Volume system*,

Forge Weight button opens the *forge weight estimation* sub module,

Flash Weight button opens the *flash weight estimation* sub module,

Material Wastages button opens the *waste material estimation* sub module,

Material Cost button opens the *forging material cost estimation* sub module.

Easy-Volume system can be used to calculate the forge volume. *Easy-volume* system includes a menu, where the primitive geometric elements can be selected. The elements can also be opened by selecting the required shapes from the picture shown Figure 6.10. For the sample part, the forge weight is known, so there is no need to use the *Easy-Volume* system. By using the *Forge Weight* button from the menu, the *forge weight estimation* sub module comes as shown in Figure 6.11. The density should be input or the material type should be selected. For the particular sample estimation process, the forge weight is input as 6950 gf. By using the *Next* button *or* clicking the *Flash Weight* button from the menu, *flash weight estimation* sub module opens, as shown in Figure 6.12. The user should input the periphery length of the forging at the parting plane. For the sample forging the flash length of 521 mm and for the middle section an additive flash area of 5300 mm^2, obtained from the technical drawing, are input to the software. The software estimates the flash weight. If desired, the user may also input the flash width and the flash thickness other than the recommended values.
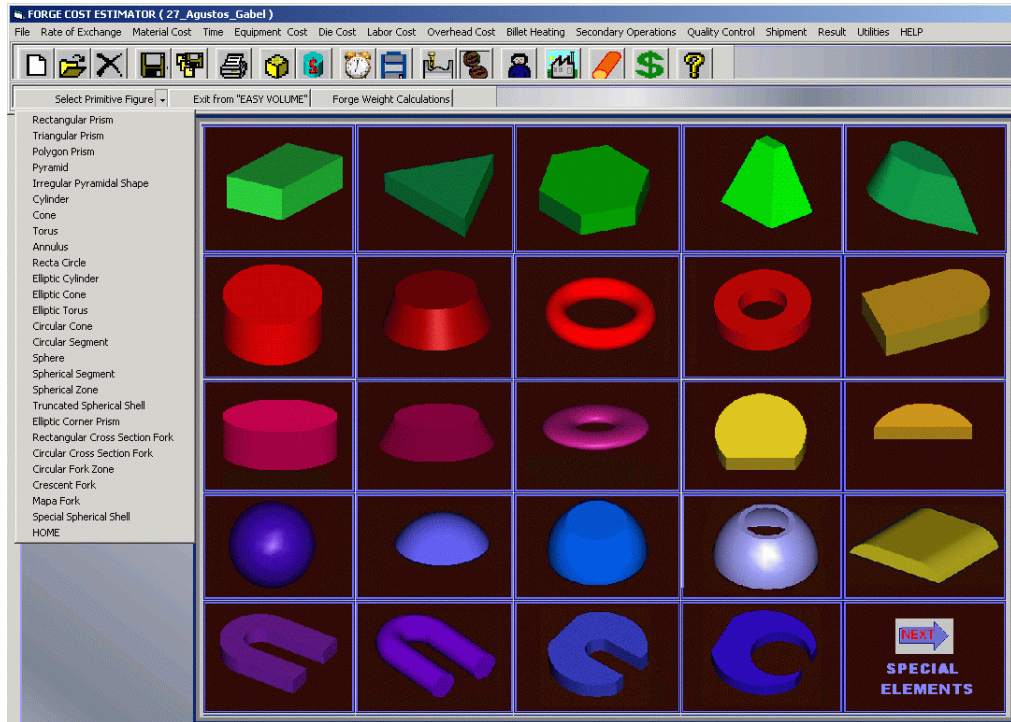
Figure 6.10 - *Easy-Volume* System Primitive Elements
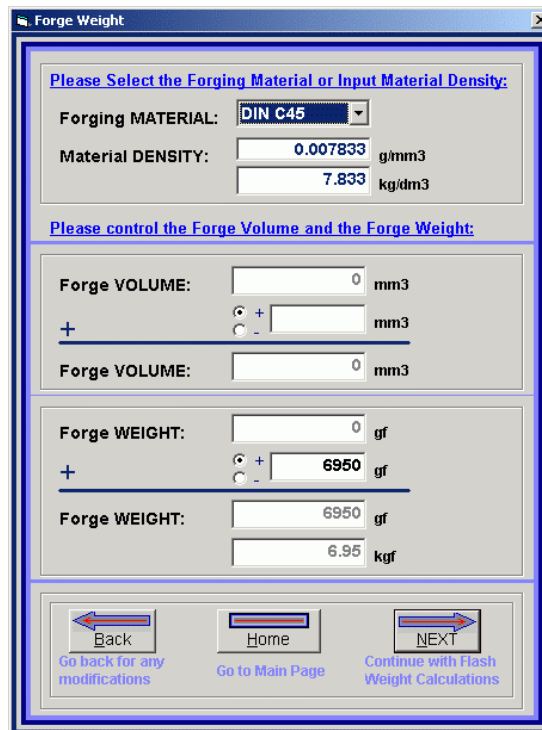
Figure 6.11 - Forge Weight Estimation Sub Module

Figure 6.12 - Flash Weight Estimation Sub Module

By using the *Next* button *or* clicking the *material wastages* button from the menu, *material wastages weight estimation* sub module opens as shown in Figure 6.13. The company default wastage parameters will come automatically. The user can select the desired material wastage sources and change the percentage values.

By clicking the *Next* button *or* clicking the *Material Cost* button from the menu, the *forging material cost estimation* sub module becomes active as shown in Figure 6.14. The user may input the unit kgf forging material cost or software can obtain the value from the material database. The user should select the billet cross-section type, select the material type that are available from the material database and input the billet cross-section dimensions. For the sample cost estimation process, C45 material with square cross section is selected and 120

mm is input as edge length value. When *calculate* button is used, the convenient material company, the cheapest material cost, the billet length and the unit forging material cost is obtained. If the *material database* button is used, the *forging material database* becomes available. The user can edit the *forging material database*. The user should control the material costs regularly for price updating. The changes in forging material database for particular estimation processes will only be reflected to the same estimation file. For stationary changes, the database in set up file, where the company cost data is saved, should be changed. The *material database* can accept the cost data in different currency units.

Figure 6.13 - Material Wastages Weight Estimation Sub Module

Figure 6.14 - Material Cost Estimation Sub Module

Figure 6.15 content:

MATERIAL COST DATABASE

CIRCULAR SECTION — SHEET 1:
DATE: 9/11/2002
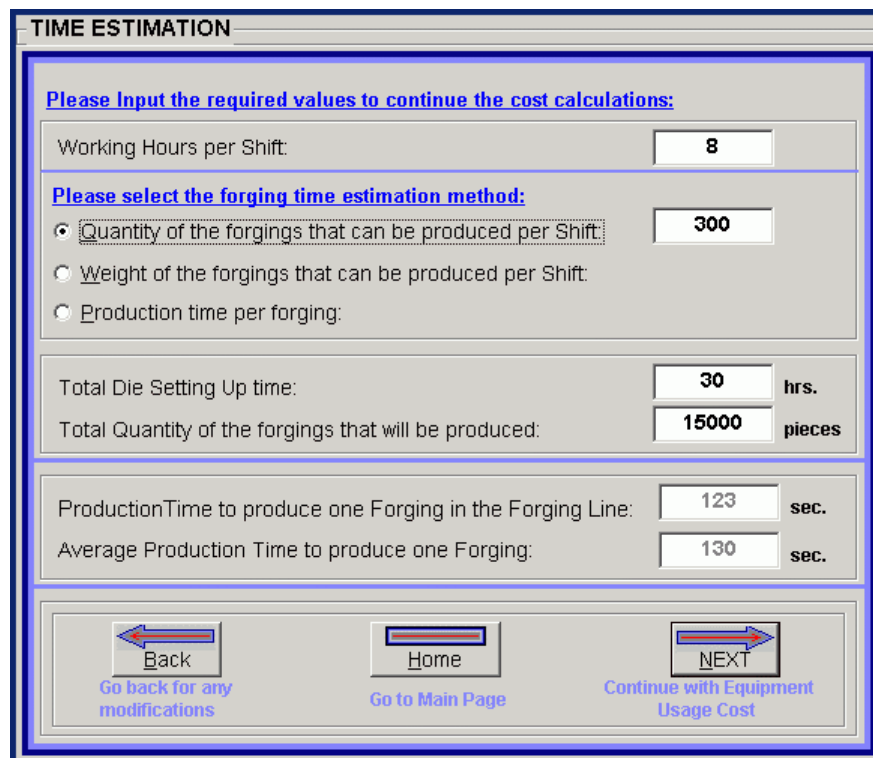
Materials:	Manufacturer:	Çemtas	Çemtas	Çemtas	Asil Çelik	Asil Çelik	Asil Çelik	Europa	Europa	Europa	Europa
	Currency Unit:	TL	TL	TL	TL	TL	TL	€	€	€	€
	Max Diameter:	16	80	120	22	70	220	10	100	200	300
SAE (1010-1090)		1613000	1613000	1740000	1710000	1710000	1845000	1.3	1.3	1.5	1.5
DIN St. 52 - 3		1213000	1213000	1340000	1545000	1545000	1670000	1.1	1.1	1.42	1.53
DIN C (10-60)		1670000	1670000	1745000	1710000	1710000	1845000	1.3	1.3	1.5	1.5
EN15S		1613000	1613000	1740000	1710000	1710000	1845000	1.3	1.3	1.5	1.5
AFNOR XC(18-55)		1710000	1710000	1845000							
AF (42-70)		1545000	1545000	1670000						1.3	
DIN 27MnSi5		1670000	1670000	1745000	1545000	1545000	1670000	1.3	1.3	1.5	1.5
DIN 30 Mn5		1670000	1670000	1745000	1710000	1710000	1845000	1.3	1.3	1.42	1.53
DIN (16-20) MnCr5		1670000	1670000	1745000	1710000	1710000	1845000	1.3	1.3	1.5	1.5
DIN (16-20) MnCrS5		1670000	1670000	1745000	1710000	1710000	1845000	1.3	1.3	1.5	1.5
DIN (16-27)MC6		1613000	1613000	1740000	1710000	1710000	1845000	1.3	1.3	1.5	1.5
SAE 8620, DIN 21NiCr		1613000	1613000	1740000	1834000	1834000	1979000	1.35	1.35	1.5	1.55
SAE 8622		1757000	1757000	1681000	1834000	1834000	1979000	1.3	1.3	1.5	1.5
DIN 13 NiCr6		1850000	1850000	1846000	1834000	1834000	1979000	1.3	1.3	1.5	1.5
SAE 3115		1613000	1613000	1740000	1710000	1710000	1845000	1.3	1.3	1.5	1.5
DIN 15 CrNi6		1850000	1850000	1846000	1834000	1834000	1979000	1.3	1.3	1.5	1.5
DIN 19 CN 6		1850000	1850000	1846000	1834000	1834000	1979000	1.3	1.3	1.5	1.5
DIN (10-35) NC5		1850000	1850000	1846000	1834000	1834000	1979000	1.3	1.3	1.5	1.5
DIN 17 CrNiMo6		1613000	1613000	1740000	1710000	1710000	1845000	1.3	1.3	1.5	1.5
DIN (34-42) CrMo(S)4		1670000	1670000	1745000				1.3	1.3	1.5	1.5
SAE 4140		1613000	1613000	1740000				1.3	1.3	1.5	1.5
DIN (25-42) Cr4		724000	724000	642000				0.5	0.5	0.45	0.4
DIN (34-41) Cr4		1850000	1850000	1846000				1.3	1.3	1.5	1.5

Figure 6.15 - Material Cost Database

The next module is the *Forging Time Estimation Module* shown in Figure 6.16. The structure of this module has been explained in Figure 5.3. Time estimation method should be selected and the required values should be input. If equipment setting up time will be considered, total die setting up time should be input.

Figure 6.16 - Time Estimation Module

By using the *Next* button *or* using the *Equipment Usage Cost* button from the menu, *Equipment Usage Cost Estimation* module opens as shown in Figure 6.17. User should input the forging projected area at the parting plane and select the enveloping shape type and input dimensions. By using the *Area Help* button, user can get help for calculating the area. For the sample forging, the forging projected area is input as 10150 mm^2. The prism type enveloping shape is selected

and 116 mm width, 174 mm length and 105 mm height is input considering the forging part dimensions. The *calculate* button or *enter* button from the keyboard, which is always the default button in all estimation modules, should be pressed for calculation. The software suggests the 4000 tonf forging line from the *Forging Line Database. F*or this case, assuming that the 4000 tonf forging line is busy, 1600 tonf forging line is selected considering that the required forging force is not much higher than the 1600 tonf forging line capacity. The software calculates the equipment usage cost per forging by using the financial data obtained from the *Forging Line Database* shown in Figure 6.18. *Forging Line Database* and the other machine databases are similar in structure. By clicking the left and right arrows, the user can see the different data sheets. By using the *Add* button, a new data sheet is formed; by using the *Update* button, the changes in data sheet are saved; by using the *Delete* button, the data sheet is deleted; by using the *Refresh* button, the data inputs and data changes after pressing the update button are neglected, and the *Close* button closes the database.

Die Cost Menu, which is shown in Figure 6.19, includes the buttons required to open the sub modules related with the die cost estimations:

Die Material Cost button opens the *die material cost estimation* sub module,

Die Milling Cost button opens the *die milling cost estimation* sub module,

EDM Electrode Material Cost button opens the *EDM electrode material cost estimation* sub module,

EDM Electrode Milling Cost button opens the *EDM electrode milling cost estimation* sub module,

EDM Machining Cost button opens the *EDM machining cost estimation* sub module,

Die Machining Costs button opens the *die machining operations cost estimation* sub module,

Hand Working Cost, Die Heat Treatment Cost, Die Design Cost, Solid Modeling + NC Code Generation Cost buttons opens the related sub module,

DIE COST button opens the *die cost estimation results* sub module,

Milling Machines DATABASE button opens the *milling machines database*,

EDM Machines DATABASE button opens the *EDM machines database*,

Machines DATABASE button opens the m*achines database*,

Figure 6.17 - Forging Equipment Usage Cost Estimation Module

Figure 6.18 - Forging Line Database

Figure 6.19 - Die Cost Menu

By using the *Next* button *or* using the *Die Material Cost* button from the menu, *Die Material Cost Estimation* sub module opens as shown in Figure 6.20. User should select the shape of the unmachined die blocks and input the dimensions considering the forging part dimensions from the technical drawing. For the sample part, cylindrical die blocks is selected, and the convenient dimensions are input. The user should select the quantity of pair of the die blocks. For the sample part, it is assumed to use 2 pair of dies. The user should select the die material from the materials that are available in the die material database. By using the *calculate* button, the die material weight, unit kgf die material cost and the total die material cost can be obtained.

Figure 6.20 - Die Material Cost Estimation Sub Module

If the die material database button is used, the *Die Material Database* becomes available as shown in Figure 6.21. The user can edit the *Die Material Database*. Changes in the die material database for particular estimation process will only be reflected to the same estimation file. For stationary changes, the database in set up file, where the company cost data is saved, should be changed. The *Material Database* can accept the cost data in different currency units.

MATERIAL TYPE:	Material Density(g/mm3):	Kgf COST:	Currency Unit:
	DIE MATERIAL	DATABASE	
S4	0.00779	4000000	TL
S5	0.00779	4000000	TL
O1	0.0078	5000000	TL
O2	0.0079	4500000	TL
O7	0.00779	4	€
A2	0.00788	3.5	€
A4	0.00779	3.6	€
A5	0.00779	3.5	€
A6	0.0078	4	$
H11	0.0079	5	$
H12	0.00779	3.1	$
H13	0.00788	4	$
H14	0.00779	3	$
H15	0.00779	4	$
H16	0.0078	3	$
H20	0.0079	3	$
T1	0.00779	4	$
T2	0.00788	2.9	$
1.2714 (DIN)	0.00779	3.1	$
1.2344 (DIN)	0.00788	3	$

Figure 6.21 - Die Material Database

The next module is the *Die Milling Cost Estimation* sub module *s*hown in Figure 6.22. In the flow diagram Figure 5.6, the milling cost estimation procedure is given. The user should input the cutting parameters for rough and if required for the finish cutting. The user should select the milling machine from the milling machine database, which is shown in Figure 6.23. If *calculate* button is used, the total cutting time, milling machine usage cost and the operator cost can be obtained. If required, cutting tool cost can be input by the user. *Area Help* button
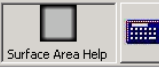
opens the area help and the *calculator* button opens the calculator for area calculations. In Figure 6.24, *EDM Electrode Material Cost* sub module and in Figure 6.25 *EDM Electrode Milling Cost* sub module is shown, which are similar sub modules to *Die Material Cost* sub module and *Die Milling* sub modules.

Figure 6.22 - Die Milling Cost Estimation Sub Module

Figure 6.23 - Milling Machines Database

Figure 6.24 - EDM Electrode Material Cost Sub Module

Figure 6.25 - EDM Electrode Milling Cost Sub Module

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The next module is the *EDM Machining Cost Estimation* sub module *s*hown in Figure 6.26. The user should select the EDM Machine that is available in the *Electric Discharge Machining Database.* Machine operation time should be input by the user. Using the calculate button, hourly machine usage cost, standard hourly operator cost, machine usage cost and the operator cost can be obtained. By using the *Next* button *or* using the *Die Machining Cost* button from the menu, *Die Machining Cost Estimation* sub module opens as shown in Figure 6.27. The user can add, up to ten different machine usage costs. The next module shown in Figure 6.28 includes the cost calculations related with the die hand finishing, die heat treatment, die design, die solid modeling and the NC Code generation cost. The user should input the hand finishing time. In Figure 6.29 *Die Cost Results* sub module is shown. By using this sub module, the user can see the results of the die cost calculations and the percentages of each cost item.

Figure 6.26 - EDM Machining Cost Sub Module

Figure 6.27 - Die Machining Sub Module

Figure 6.28 - Die Hand Finishing Sub Module

Figure 6.29 - Die Cost Results

The next cost item is the labor cost. The average production time per forging comes from the *Time Estimation* module shown in Figure 6.30. The quantity of the labors in the forging line, which is selected in *Equipment Usage Cost Estimation* module, comes from the *Forging Line Database.* If required the user can change the labor quantity. The hourly direct labor cost is obtained from the company cost data and generally there is no need to change it. Labor cost per forging is the result of *Labor Cost Estimation* module.

Figure 6.30 - Labor Cost Estimation Module

The Overhead Cost Estimation module is the next module shown in Figure 6.31. The overhead parameters come from the previous modules and the company cost data, as explained in Figure 5.13. Generally there is no need to change the overhead parameters each time, which come from the accountancy department of the company. Periodic maintenance may be applied in the set up file or the company cost data, for stationary changes. The Equations 4.6 and 4.7 is used in overhead cost calculations. The user may input the overhead rate manually, if required. The output is the overhead cost that should be reflected per forging.

Figure 6.31 - Overhead Cost Estimation Module

The Billet Heating Cost Estimation module shown in Figure 6.32 calculates the billet heating cost per forging automatically, considering the forging weight and the furnace type.

The Secondary Operations Cost Estimation module shown in Figure 6.33 calculates the secondary operations cost per forging. The user should select the required operations to be applied to the forgings. For the sample forging, tumbling process and then zinc coating is required for preventing from corrosion. The zinc coating cost per kg material learned from the subcontractor firm is input. Tumbling cost comes from the company cost data.

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Figure 6.32 - Billet Heating Cost Estimation Module

Figure 6.33 - Secondary Operations Cost Estimation Module

The Q*uality Control Cost Estimation* module shown in Figure 6.34 calculates the quality control cost per forging. The required quality control operations should be selected, the application quantity and operation cost per forging should be input by the user. Default company cost data per forging can give an idea to the user.

Figure 6.34 - Quality Control Cost Estimation Module

Figure 6.35 - Shipment Cost Estimation Module

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In S*hipment Cost Estimation* module shown in Figure 6.35 the user should, input the packaging cost if required. The module calculates the total load and required transportation container quantity. Giving the transportation details to the transportation firms, the transportation cost may be obtained and input to the software. The output is the shipment cost per forging and the total shipment cost. There is a help sub module for giving information about the transportation incoterms.
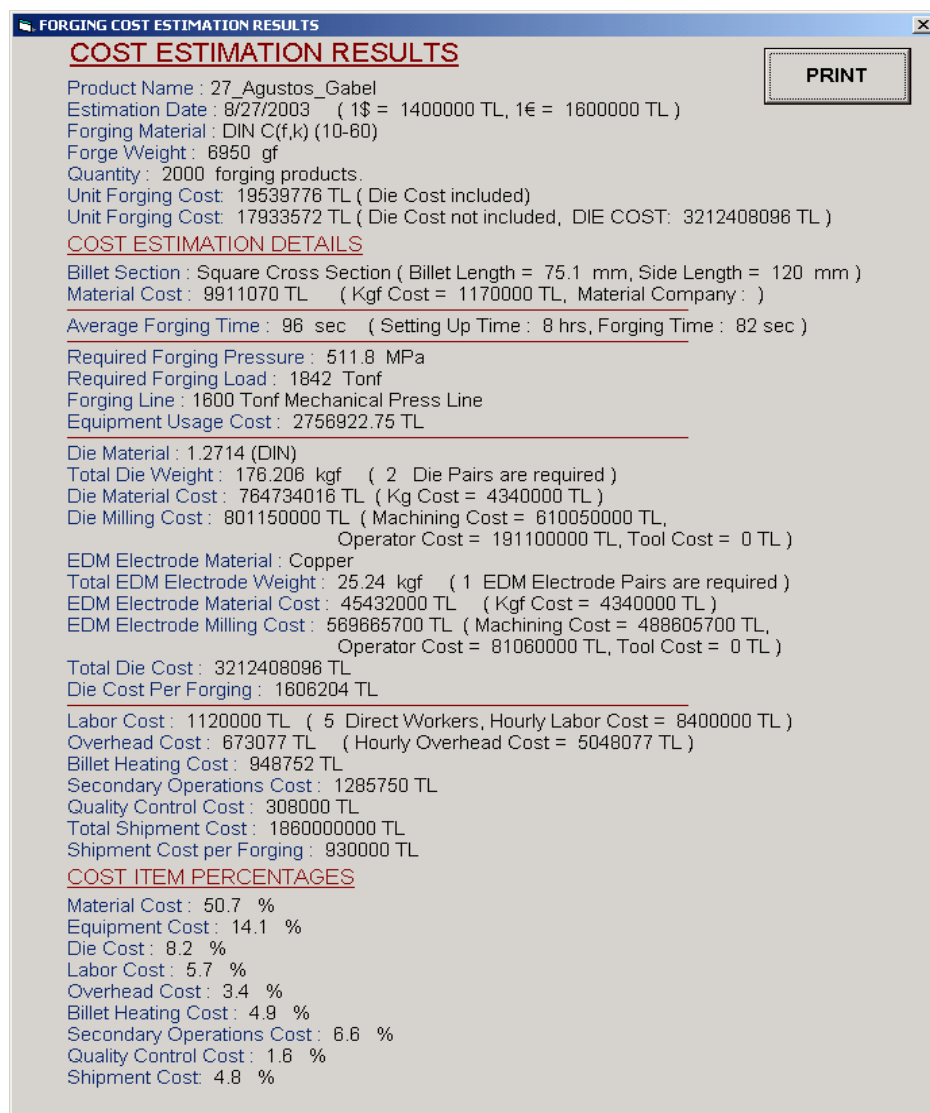

Figure 6.36 - Forging Cost Estimation Results Module

In Figure 63.6, the *Cost Estimation Results* module is shown. By using the *print* button, the results may be printed. The forging cost including the die cost and excluding the die cost are calculated, because in the industry, the die cost may be reported to the customer separately [2]. The results include all of the cost items. Percentage values of the cost items are given for serving as a general control mechanism. The software also includes different help and utility facilities.

6.3 Results of the Sample Cost Estimation Process

The results of the sample estimation process are shown in Figure 6.36. The outputs of the several runs made in the forging industry, are found to be reasonable by the cost estimators [2]. The cost estimators in Aksan Forging Company has been satisfied with the capabilities and the results of the software. The sample test run has been achieved in 25 minutes. If the forging weight had been calculated by the software, it would have taken a longer time. In this sample calculation, many of the cost data that are input are not the exact values, which are used in the Aksan Forging Company, because of the company's secrecy policy. The values that are input are the approximate values, so they can give an approximate idea. Actually, each company has its own cost data since every company have a different structure. When a new company will use this software, the software will allow the set up file to be altered according to the company cost data. The forging equipment and machinery databases may also be changed.

With this software, the cost estimation process is automated as much as possible to relieve the job of the cost estimator. However, the inputs like forging time and quantity of required dies depends on the knowledge and the expertise of the cost estimator. As it was stated in Section 1.5, the cost estimation software can be a tool to complement the cost estimator and not a substitute for the experienced estimator. The accuracy of the cost estimates depends on the cost estimator and the data inputs. If the inputs are realistic and reasonable, the cost estimation will be accurate and good.

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CHAPTER 7

CONCLUSIONS AND FUTURE WORK

7.1 Conclusions

The conclusions of this study can be listed as follows:

1) Throughout the study that is described in this thesis, a computer aided cost estimation software has been developed. The software is capable of performing the cost estimation process for hot forgings. The software, named "*Forge Cost Estimator*" has been developed in MS Visual Basic 6.0 language.

2) About 13000 lines of codes have been written and above 60 forms have been prepared to constitute the "*Forge Cost Estimator*" software. The program code has been tried to be written in a simple, easy to understand logic and format. The software's modular architecture enables future updates and modifications.

3) The software has various databases prepared by using MS Access and MS Excel. The forging equipment and machining equipment databases include forging and machining equipments technical properties and financial data. The material databases include the cost related material data and some technical properties like the density.

4) At the initial stage of the software development, the aimed properties of the estimation software are determined. The aims introduced in Section 5.1, are always considered during the development of the software. A user friendly and easy to use program, which follows standard Windows software conventions and free from errors as possible, has been developed.

5) In order to give reliable estimates, forging product is divided into its cost and work elements and *"forging work breakdown structure"* is prepared. The selected cost estimation method used in the software is the bottom-up cost estimation method in which, cost items defined in the work breakdown structure are calculated and summed up in an additive structure as explained in Chapter 4.

6) "Forge Cost Estimator" software includes different modules for estimation of different forging cost items. The cost items that are calculated by using different modules of the software are summed up to reach to the forging product cost.

7) In forging cost estimation, determination of the forge volume is very critical to find the required press or hammer capacity, flash allowance, scale loss, billet weight and the forging material cost. In this study, by using volume fragmentation method in which the forge volume is fragmented into simple geometrical shapes for summing up the volumes later on, has been used for the forge volume estimation. Based on volume fragmentation method, a new software system for the volume estimation process, named "***Easy-Volume***" has been developed. After analysis of the forging shape classification and coding systems and various practical applications of the method on forgings in correlation with the forging industry; 24 primitive elements including simple geometrical shapes and some more complex shapes are determined to speed up and ease the volume estimation process. The system has been tested for several parts and an average error value of 4.5% is obtained, which is a quite satisfying value. The results of those studies and a case study are given in Chapter 3.

8) The forging equipment cost estimation module calculates the forging pressure, load and the shape complexity and suggests to the user the most convenient forging line from the forging line database, considering the forging weight, load and the dimensional forging limitations of the forging equipment.

9) By using the die cost estimation module, cost of the dies can be obtained including the material cost, machining costs and other related costs.

10) Controls and checks are done by real life applications in Aksan Forging Company as a pilot study. According to the feedbacks from real life users, various corrections in the software have been made. The software has been tested for several forgings and satisfactory estimations have been achieved. A sample run has also been presented in Chapter 6.

11) Normally, the cost estimation procedure with *"Forge Cost Estimator"* can be completed in less than an hour, which can be done in longer periods by manual cost estimation. It is observed that cost estimation time is reduced by the use of this program.

12) The software has the property of foreign exchange capability for US Dollar ($), Euro (€) and a third currency unit, which can be defined by the user. In real life, different currency units may be used for different cost items. *"Forge Cost Estimator"* enables the user to work with different currency units in different cost modules.

13) The software includes an installation pack, which makes it possible to install the program on desired computer. Installation pack includes the required files for performing the cost estimation process.

14) With this software, the forging cost estimation process is automated as much as possible to relieve the job of the cost estimator. However, the estimation software can be a tool to complement the cost estimator and it will not be a substitute for the ability of the estimator to input reasonable inputs based on the judgment and experience. Therefore, the accuracy of the cost estimates depends on the cost estimator and the quality of the inputs. If the inputs are realistic and reasonable, the cost estimation will be accurate.

15) To the author's knowledge *Forge Cost Estimator* software is the only application in this field, which uses bottom-up cost estimation method and the volume estimation module *"Easy-Volume"* is a newly proposed system for volume estimation purpose.

7.2 Future Work

For future development, an interaction of the *Forge Cost Estimator* with some of the commonly used CAD software packages (Pro/Engineer, Uni-Graphics, Catia) can be prepared. By this way, if the CAD model is provided by the customer, the volume of the forging can be directly obtained.

If required, new primitive figures of complex parametric shapes that are often used in a forging company may be added to *"Easy-Volume"* volume estimation system for speeding up the estimation process.

The "Forge Cost Estimator" may be integrated with machining cost estimation software, which is designed for the detailed machining cost estimation process, including a machining database of different types of traditional and non-traditional manufacturing equipment. By this way the effectiveness of the forging die cost estimation process may be improved.

The cost estimation software may be integrated with cost accounting software to compare the cost estimations with the real costs. A historical database structure may be formed for collecting the estimation cost data and the real cost data in a systematic way. With the aid of a learning system, the software may become capable of taking the real cost data as reference for better estimations and the historical data may be corrected after each estimation.

A cost estimation methodology developed in the past can represent the today's requirements but for future use, it must be made sure that the estimation techniques are still convenient for the firm. New manufacturing techniques and processes may change the estimation methodology. However, it can be said that *"Forge Cost Estimator"* can be a base and may guide the software designers for developing new estimation programs.

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APPENDIX A

INFORMATION ABOUT AKSAN FORGING COMPANY

Aksan Steel Forging Industry Co. Ltd. has been working on hot steel forging and machining in Pursaklar - Ankara / Turkey since 1966. Aksan is working as a supplier for automotive, machinery, electric and construction sectors. Aksan is a middle-sized company with its 125 personnel. Aksan's market share is about 10% in Turkey and 35% of the capacity has been allocated for export to foreign markets. Manufacturing continues in two separate facilities established on 3,500m^2 (AKSAN1) and 30,500m^2 (AKSAN2) area. Aksan organized its quality system according to 'ISO 9002' and is certified by BVQI.

Current capacity of Aksan is total 10,000 tons per year. Unit forging weight capability is from 0.2 kgf to 28.0 kgf. There are three forging lines in Aksan1 and two forging lines in Aksan 2.

- AKSAN1 forging lines are, 1000 tonf mechanical press line, 750 tonf power drop hammer line and 250 tonf mechanical press line.

- AKSAN2 forging lines are, 4000 tonf hydraulic press line and 1600 tonf mechanical press line.

Forging lines includes, 25, 160, 200, 250, 320, 500 tonf trimming and preforming presses, also various induction heaters (100-400-970kW) and fuel-oil furnaces are active . The company has a manufacturing workshop, which includes the required machines for die manufacturing.
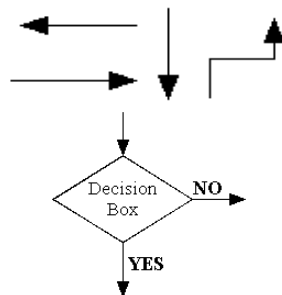
APPENDIX B

FLOW DIAGRAM SHAPES AND EXPLANATIONS
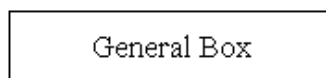
General Box may show a calculation, a result or a data input by the software from the other modules or the previous calculations.
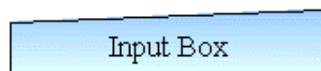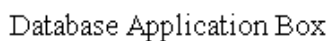
Input Box represents data input or selection by the user. It is shaded for better distinguishing from the other shapes.
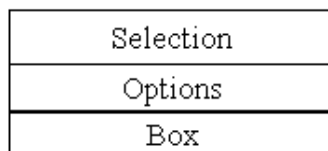
**Flow Lines and Arrows** show the sequence of the operation steps.

Decision Box represents operations in which there are two possible alternatives. One flow line enters and two flow lines (labeled yes and no) exit.

Database Application Box shows the database application and may be used to give information about database usage.

Selection Options Box may be formed of at least two or more combined boxes. The user should select one or more of the items listed in boxes. It comes after an Input Box including the directive of *"Select the related item or items"*.
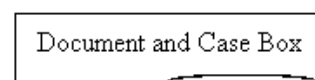
Document and Case Box shows the documentation activity or different start cases if numbered.

APPENDIX C

DEPRECIATION COST ACCOUNTING METHODS

Depreciation can be independent of use like deterioration due to corrosion, bacterial action, rotting due to environment etc. Depreciation can also be dependent of use like wearing and deterioration from use, which subjects the equipment to abrasion, vibration, impact etc. All those factors dependent or independent of use, result in the lowering of the ability of a physical asset to render its intended service [8].

An asset such as a forging press is a unit of capital and this capital looses a value over a period of time in which it is used in production. Lost capital needs to be accounted in order to determine the production cost. Expenditures of capital in this way are difficult to observe and difficult to evaluate in monetary terms. General method to account this lost is, rather than charging the entire cost as an expense at the time the asset is purchased, spreading the loss in value over the life of the asset in a systematic way. It is assumed that the value of an asset decreases yearly in accordance with one of several mathematical functions. There are different methods of accounting depreciation by using different mathematical functions. Most common depreciation accounting methods are:

- straight-line method,

- declining balance method,

- sum of the years digits method,

In all of those methods, there are some terms that should be explained. 'Book value' is a term used to represent the original value of an asset minus its

accumulated depreciation at any point in time. The book value at the end of any year is equal to the book value at the beginning of the year minus the depreciation expense charged during the year. For example, the book value at the beginning equals to the initial asset value. 'Salvage value' is a term used for the estimated final value of the asset, after all depreciation expenses are subtracted.

Following notation will be used in depreciation method formulations.

P = first cost of the asset

F = estimated salvage value

B_t = book value at the end of year t

D_t = depreciation charge during year t

n = estimated life of the asset

t = year (1,2, … ,n)

The book value is formulated as follows;

$$B_t = B_{t-1} - D_t \tag{B.1}$$

In straight-line depreciation method, it is assumed that the value of an asset decreases at a constant rate. A salvage value is estimated and according to the estimated life of the asset the depreciation in any year and the book value can be found by the following formula. The depreciation rate per year is 1/n. The depreciation in any year and the book value is:

$$D_t = (P - F) / n \tag{B.2}$$

$$B_t = P - t \,.\, (P - F) / n \tag{B.3}$$

Table B.1 - Straight Line Depreciation Method

End of year t	Depreciation charge during year t	Book value at the end of year t
0	-	P
1	$(P-F)/n$	$P-((P-F)/n)$
2	$(P-F)/n$	$P-2((P-F)/n)$
3	$(P-F)/n$	$P-3((P-F)/n)$
t	$(P-F)/n$	$P-t((P-F)/n)$
n	$(P-F)/n$	$P-n((P-F)/n)$

In declining balance method, it is assumed that the value of an asset decreases at a faster rate in the early portion of its service life than in the latter portion of its life. A fixed percentage generally called depreciation rate is multiplied with the book value of the asset to determine the depreciation in that year. The depreciation in any year and the book value is

$$D_t = R.(1 - R)^{t-1}.P \qquad (B.4)$$

$$B_t = (1 - R)^t.P \qquad (B.5)$$

Table B.2 - Declining Balance Depreciation Method

End of year t	Depreciation charge during year t	Book value at the end of year t
0	-	P
1	$R \times B_0 = R(P)$	$(1-R)B_0 = (1-R)P$
2	$R \times B_1 = R(1-R)P$	$(1-R)B_1 = (1-R)^2 P$
3	$R \times B_2 = R(1-R)^2 P$	$(1-R)B_2 = (1-R)^3 P$
t	$R \times B_{t-1} = R(1-R)^{t-1} P$	$(1-R)B_{t-1} = (1-R)^t P$
n	$R \times B_{n-1} = R(1-R)^{n-1} P$	$(1-R)B_{n-1} = (1-R) P$

In declining balance method, the depreciation rate is usually selected considering its effect on income taxes. The maximum allowable rate that may be used is double of the straight-line rate, which is $2(1/n)$. Such kind of a depreciation method is called as double declining balance method.

In sum of the years digits method, it is assumed that the value of an asset decreases at a decreasing rate. The sum of the years digits method produces larger depreciation charges in the early life of the asset. Depreciation rate decreases through time and it is multiplied with a fixed amount, which is the first cost of the asset minus the salvage value (P-F). This is in contrast to the double-declining method in which a fixed rate is multiplied with a decreasing book value.

The depreciation in any year and the book value is :

$$D_t = \frac{n-t+1}{n \cdot \frac{(n+1)}{2}} \cdot (P - F) \tag{B.6}$$

$$B_t = P - \frac{(P-F)}{n \cdot \frac{(n+1)}{2}} \cdot \left(\sum_{j=n-t+1}^{n-t} j \right) = (P-F) \cdot \left(\frac{n-t}{n} \right) \cdot \left(\frac{n-t+1}{n+1} \right) + F \tag{B.7}$$

Sum of the years digits method is a complex method to apply, but it produces a value-time curve that approximates the decrease in value of many categories of assets [8].

APPENDIX D

PARAMETERS AND DETAILS FOR "EASY-VOLUME" PRIMITIVE ELEMENTS

In this Appendix the parameters and the details of the "*Easy-Volume*" volume estimation system's primitive elements will be presented. Firstly, the figure of the primitive element and then the meaning of the letter abbreviations, the volume calculation formula and the critical limitations that are considered in the software are given.
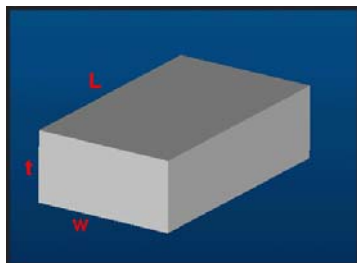
Figure D.1 - Rectangular Prism

w, t , L : side lengths of the rectangular prism

Volume: $V = w . t . L$
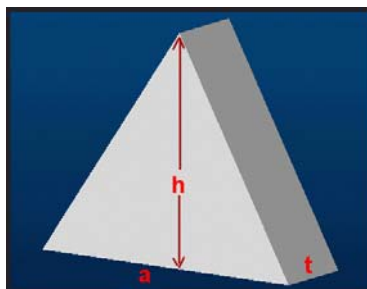
Figure D.2 - Triangular Prism

a, t : side lengths of the base plane

h : height of the side triangle

Volume: $V = a . h . t / 2$
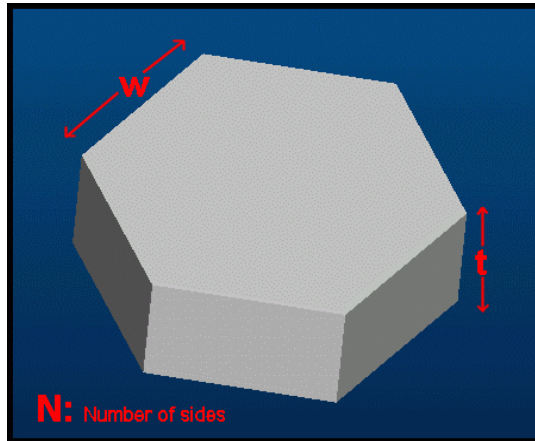
w : side lengths of the base plane

t : thickness of the prism

N : number of sides

Figure D.3 - Polygon Prism

Volume: $V = (1/4) \cdot (t \cdot N \cdot W^2 \cdot \cot(180^0 / N))$

Limitations: i) $N > 3$ ("N" value should be greater than 3)
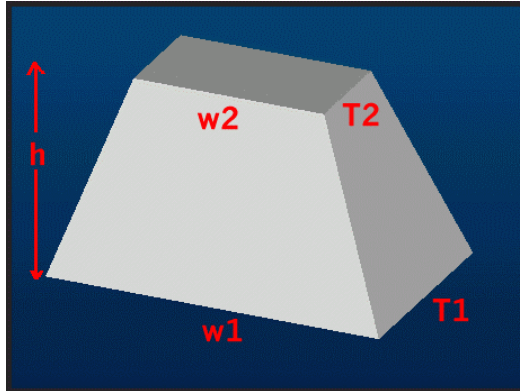
w1, T1 : side lengths of the lower side with a bigger area

w2, T2 : side lengths of the upper side with a smaller area

h : height of the prism

Figure D.4 - Pyramid

Volume: $V = (w1 \cdot T1 + w2 \cdot T2 + \sqrt{w1 \cdot T1 \cdot w2 \cdot T2})(h/3)$

Limitations: i) $w2 \leq w1$

ii) $T2 \leq T1$

A1: upper surface area

A2: lower surface area

h : height

Volume:
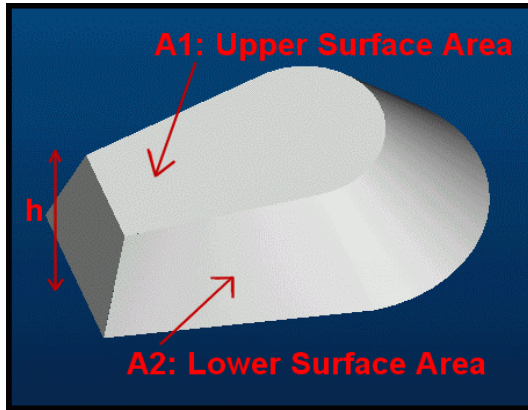
$$V = (A1 + A2 + \sqrt{A1 \cdot A2})(h/3)$$

Figure D.5 - Irregular Pyramidal Shape
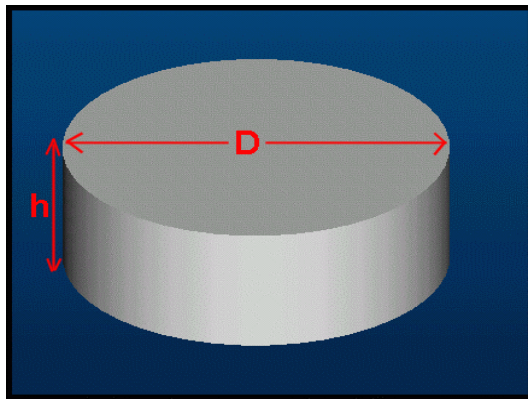
D: diameter of the cylinder

h: height of the cylinder

Volume: $V = (\Pi \cdot h \cdot D^2)/4$

Figure D.6 - Cylinder
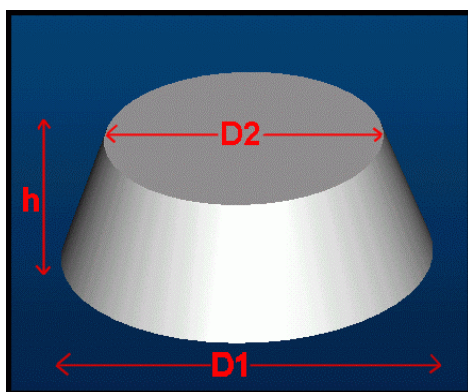
D1: diameter of the lower circle

D2: diameter of the upper circle

h: height of the cone

Volume:

$$V = (\Pi \cdot h / 12) \cdot (D1^2 + D2^2 + D1 \cdot D2)$$

Figure D.7 - Cone

D1: outer diameter of the Torus

D2: inner diameter of the Torus

Volume:

$$V = (\Pi^2 / 64) . (D1 + D2) . (D1 - D2)^2$$

Limitations: i) $D1 > D2 > 0$
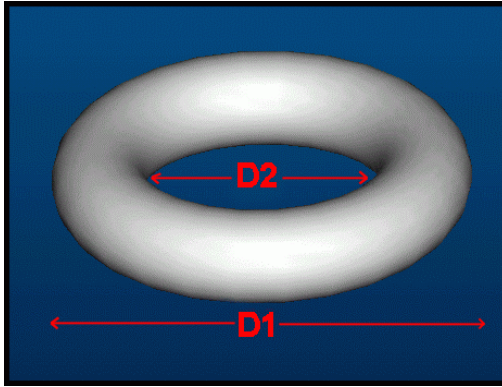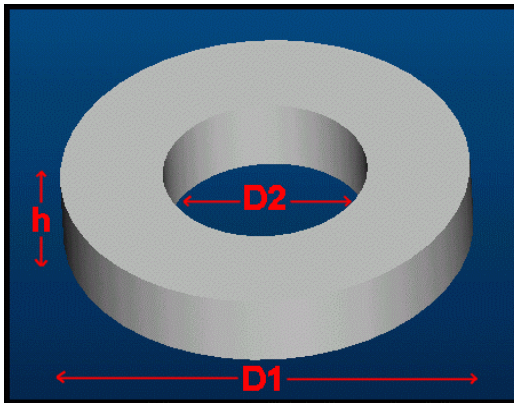
Figure D.8 - Torus

D1: outer diameter of the Annulus

D2: inner diameter of the Annulus

h : height of the Annulus

Volume: $V = (\Pi . h / 4) . (D1^2 - D2^2)$

Limitations: i) $D1 > D2$

Figure D.9 - Annulus

w : width of the rectangle

L : length of the rectangle

t: thickness
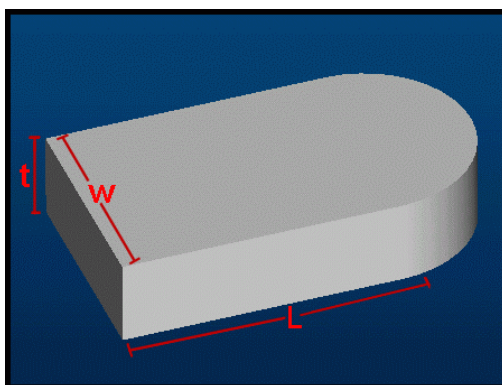
Volume: $V = t . (w . L + \Pi . w^2 / 8)$

Figure D.10 - Recta Circle

r1 : the bigger radius of ellipse

r2 : the smaller radius of ellipse

h : thickness
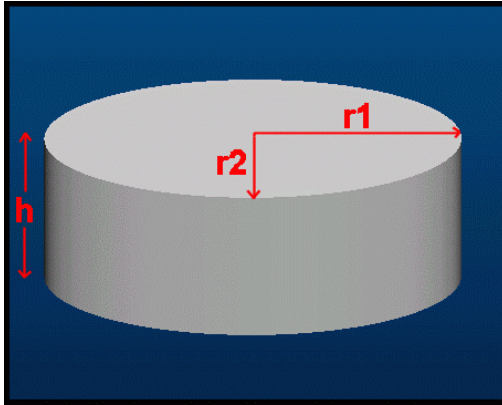
Volume: $V = \Pi \cdot r1 \cdot r2 \cdot h$
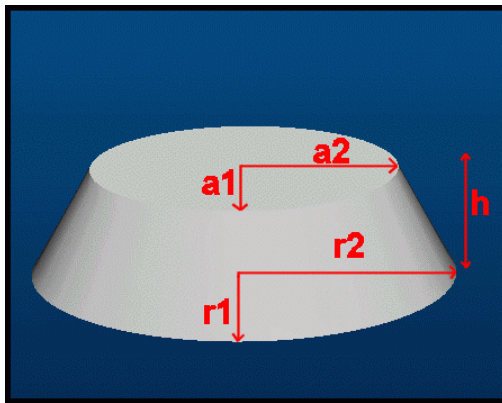
Figure D.11 - Elliptic Cylinder

r1 : the smaller radius of the bottom side with the greater area

r2 : the bigger radius of the bottom side with the greater area

a1 : the smaller radius of the top side with the smaller area

a2 : the bigger radius of the top side with the smaller area

Figure D.12 - Elliptic Cone

h : height of the elliptic cone

Volume: $V = (\Pi \cdot h / 3) \cdot (r1 \cdot r2 + a1 \cdot a2 + \sqrt{a1 \cdot a2 \cdot r1 \cdot r2})$

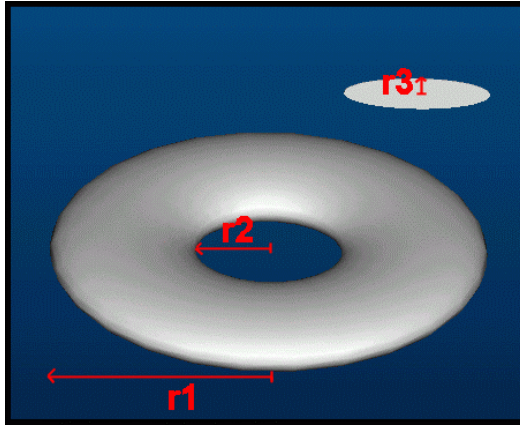**Limitations:**   i) $a1 \leq r1$

ii) $a2 \leq r2$

r1 : the smaller radius of the Torus

r2 : the bigger radius of the Torus

r3 : the vertical radius of the Torus cross section

Volume: $V = (\Pi^2 . r3 / 2) . (r1 - r2) . (r1 + r2)$
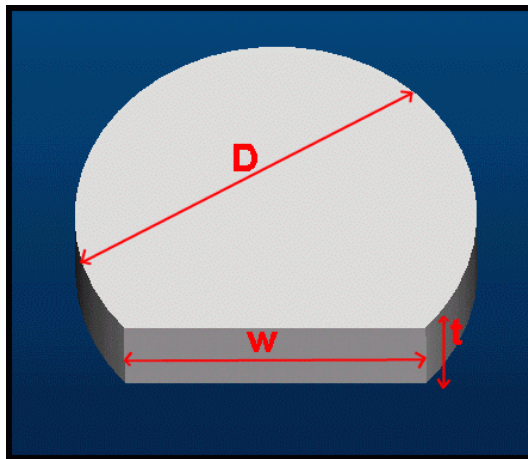
Limitations: i) $r1 \geq r2 > 0$

Figure D.13 - Elliptic Torus

D : diameter of the circle

t : thickness of the circular zone

W : width of the cut area

Figure D.14 - Circular Zone

Volume: $V = (\Pi . D^2 . t / 4) - (\frac{1}{2} . t . r^2 . (X - \operatorname{Sin} X))$

where, $X = 2 . \tan^{-1} (w / 2. \sqrt{(D^2 - W^2)})$

Limitations: i) $D \geq W > 0$

Explanation: Side surface area is equal to the area formed by the circle segment area subtracted from the circle area. Multiplying with the thickness, the volume can be obtained. The value of X is in radians.
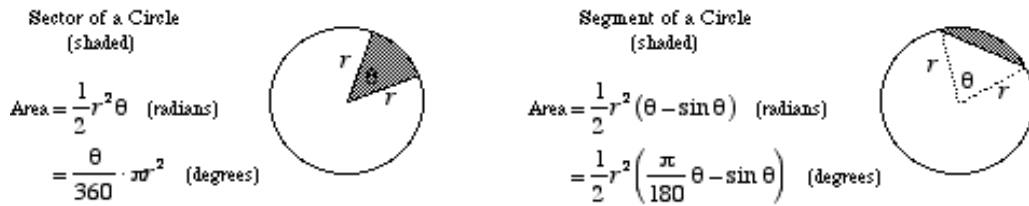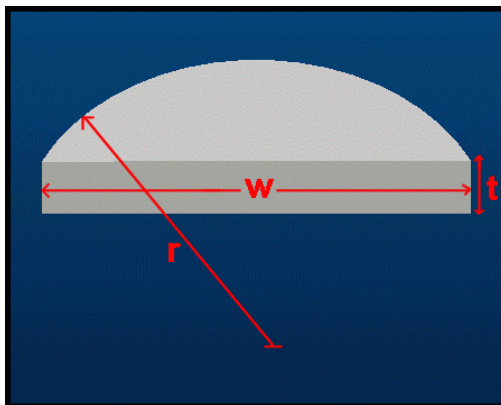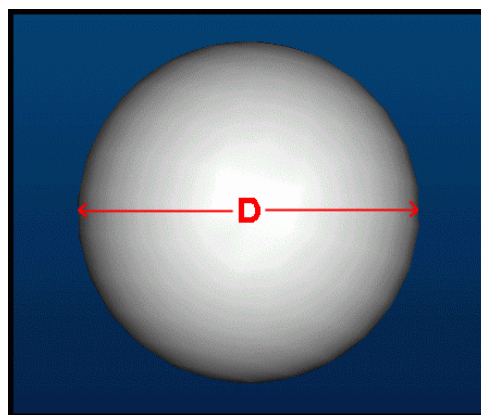
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Sector of a Circle
(shaded)

$$\text{Area} = \frac{1}{2}r^2\theta \quad \text{(radians)}$$

$$= \frac{\theta}{360} \cdot \pi r^2 \quad \text{(degrees)}$$

Segment of a Circle
(shaded)

$$\text{Area} = \frac{1}{2}r^2(\theta - \sin\theta) \quad \text{(radians)}$$

$$= \frac{1}{2}r^2\left(\frac{\pi}{180}\theta - \sin\theta\right) \quad \text{(degrees)}$$

Figure D.15 - Circular Zone Explanation

r : radius of the circle

t : thickness of the circular zone

W : width of the cut area

Figure D.16 - Circular Segment

Volume: $V = (\frac{1}{2} \cdot t \cdot r^2 \cdot (X - \sin X))$
 where, $X = 2 \cdot \tan^{-1}(w / 2 . \sqrt{(r^2 - W^2/4)})$

D : diameter of the Sphere
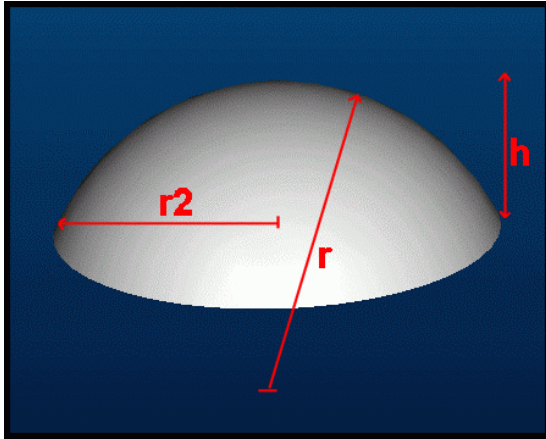
Volume: $V = (\Pi \cdot D^3 / 6)$

Figure D.17 - Sphere

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The *Spherical Segment* is a cut half sphere.

The *Spherical Zone* is a cut half sphere, from both sides.

r : radius of the Sphere

r2 : radius of the side

h : height of the Spherical Segment

Figure D.18 - Spherical Segment

Volume: $V = (1/6) \cdot \Pi \cdot h \cdot (3 \cdot r^2 + h^2)$ where, $h = r - \sqrt{(r^2 - r2^2)}$

Limitations: i) $h \leq r$

ii) $r2 \leq r$

iii) One of the "h" or "r" value is required. If both "h" and "r" value is input, "r" value is considered.
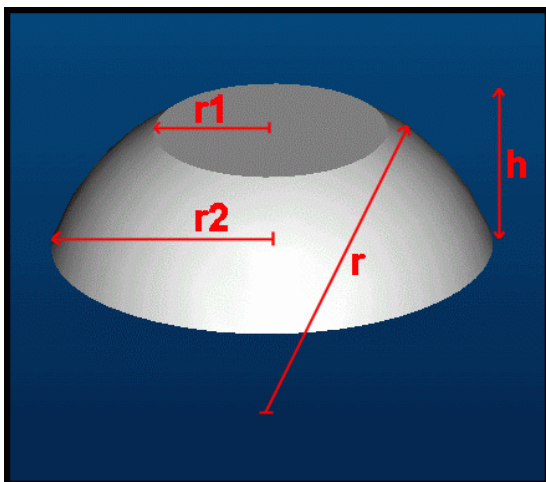

The *Spherical Zone* is a cut half sphere, from both sides.

r₁ : radius of the upper side with a smaller area.

r₂ : radius of the lower side with a bigger area.

r : radius of the sphere

h : height of the spherical zone
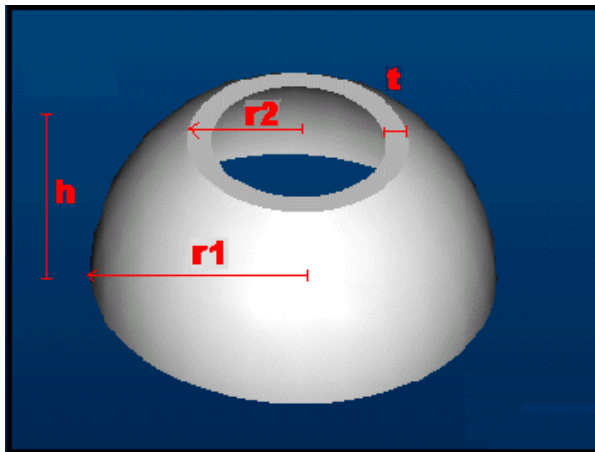
Figure D.19 - Spherical Zone

Volume: $V = (1/6) \cdot \Pi \cdot h \cdot (3 \cdot r_1^2 + 3 \cdot r_2^2 + h^2)$

where, $h = \sqrt{(r^2 - r_1^2)} - \sqrt{(r^2 - r_2^2)}$

Limitations: i) $0 \leq r_1 < r_2 \leq r$ ("r_1" value can be equal to zero, "r_2" value can be equal to "r" value)

ii) $h \leq r$

iii) One of the "h" or "r" value is required. If both "h" and "r" value is input, "r" value is considered.

r_1 : radius of the lower side with a greater area.

r_2 : radius of the upper side with a smaller area.

t : thickness of the shell

h : height of the spherical shell

Figure D.20 - Truncated Spherical Shell

Volume: $V = (1/6) \cdot \Pi \cdot [\, h1 \cdot (3 \cdot r_1^2 + 3 \cdot r_2^2 + h1^2) - h1 \cdot (3 \cdot (r_1 - t)^2 +$

$3 \cdot (r_2 - t)^2 + h1^2)]$

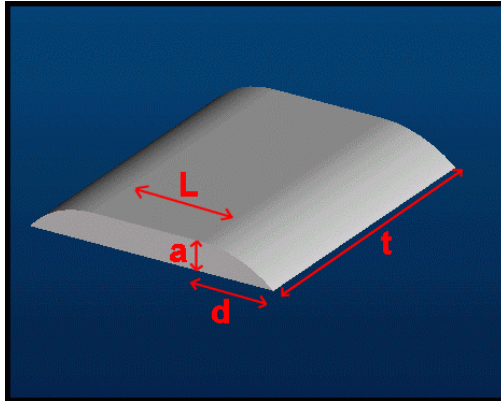**Limitations:** i) $0 < t < r_2 < r_1$

ii) $h_1 \leq r_1$

a : smaller radius of the quarter ellipse

d : bigger radius of the quarter ellipse

t : thickness of the prism

L : width of the upper smaller surface

Volume: $V = t \cdot (\Pi \cdot a \cdot d \,/\, 4 + L \cdot a)$
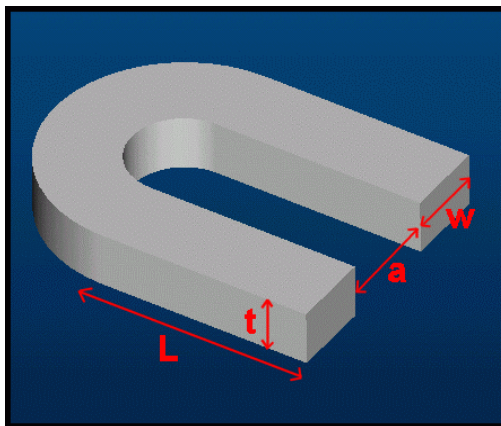
Figure D.21 - Elliptic Corner Prism

The *Rectangular Section Fork* is the shape formed with two prisms and a half annulus.
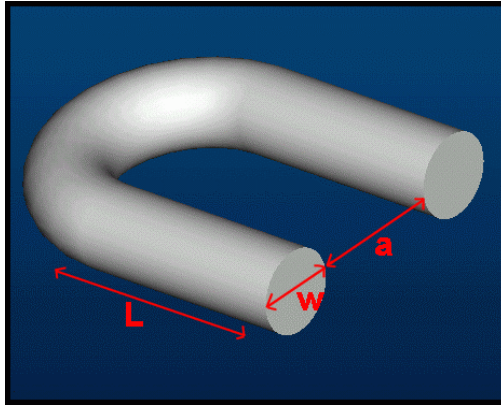
a : diameter of the inner circle

w : width of the rectangular prism

L : length of the rectangular prism

t : thickness

Figure D.22 - Rectangular Section Fork

Volume: $V = 2 \cdot w \cdot t \cdot L + \tfrac{1}{2} \cdot t \cdot \Pi \cdot [\, (w + a/2)^2 - (a/2)^2 \,]$

$$V = w \cdot t \cdot (4 \cdot L + \Pi \cdot (w + a)) \,/\, 2$$

The *Circular Section Fork* is the shape formed with two cylinders and a half torus.

a : diameter of the inner circle

L : length of the cylinder

W : diameter of the cylinder

Figure D.23 - Circular Section Fork

Volume: $V = 2 \cdot \Pi \cdot W^2 \cdot L / 4 + (\frac{1}{2} \cdot \Pi^2 / 4) \cdot [(2 \cdot (W + a) / 2) \cdot (W)^2]$

$$V = \Pi \cdot W^2 \cdot (L + \Pi (w + a) / 4) / 2$$
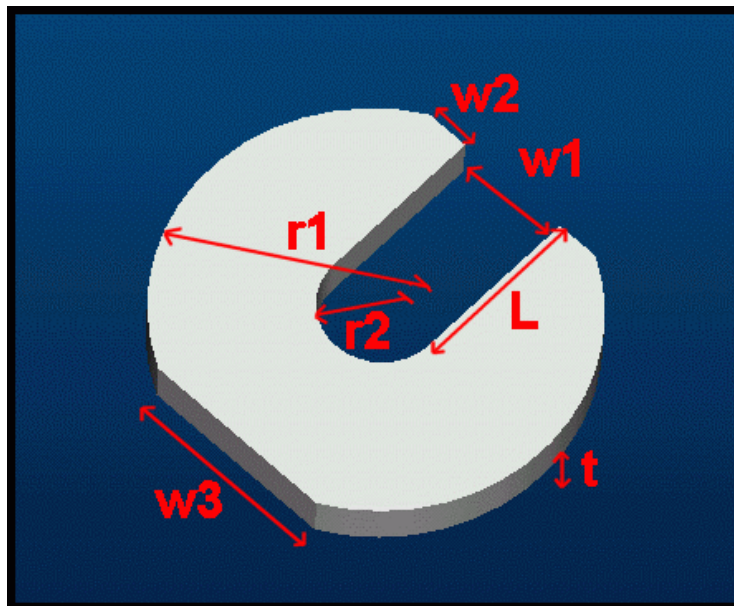

Figure D.24 - Circular Fork Zone

The *Circular Fork Zone* is a specialized form of primitive element. The explanations are given below:

r1 : diameter of the big Circle

r2 : diameter of the small Circular Segment

L : length of the Prism Slot

w1 : width of the Prism Slot and the Circular Segment

w2 : width of the tip

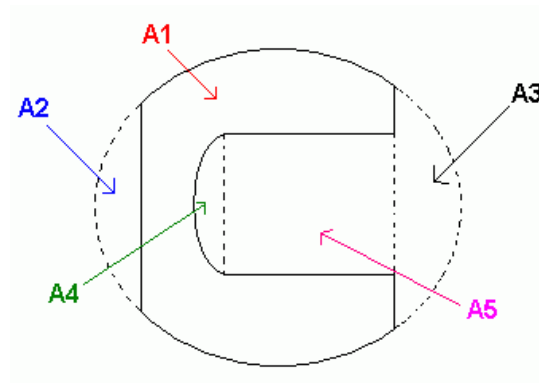**w3** : width of the outer cut Circular Segment

Figure D.25 - Circular Fork Zone Explanation

Volume: $V = (A1 - A2 - A3 - A4 - A5) \cdot t$

The Area fragmentation figure and the formula of each Area is given below:

A1 : The Area of the total Circle

A2 : The Area of the outer left Circular Segment

A3 : The Area of the outer right Circular Segment

A4 : The Area of the inner Circular Segment

A5 : The Area of the Rectangle

$A1 = \Pi \cdot r1^2$

$A2 = (\frac{1}{2} \cdot r1^2 \cdot (X_1 - Sin\ X_1))$

where, $X_1 = 2 \cdot tan^{-1}\ [w3 / 2.\sqrt{(r1^2 - W3^2 / 4)}]$

$A3 = (\frac{1}{2} \cdot r1^2 \cdot (X_2 - Sin\ X_2))$

where, $X_2 = 2 \cdot tan^{-1}\ [(w1 + 2. w2) / 2.\sqrt{(r1^2 - (w1 + 2. w2)^2 / 4)}]$

$A4 = (\frac{1}{2} \cdot r2^2 \cdot (X_3 - Sin\ X_3))$

where, $X_3 = 2 \cdot tan^{-1}\ [(w1) / 2.\sqrt{(r2^2 - w1^2 / 4)}]$

$A5 = w1 \cdot L$

Limitations: i) $r2 < r1$,　　ii) $w3 \leq 2 \cdot r1$

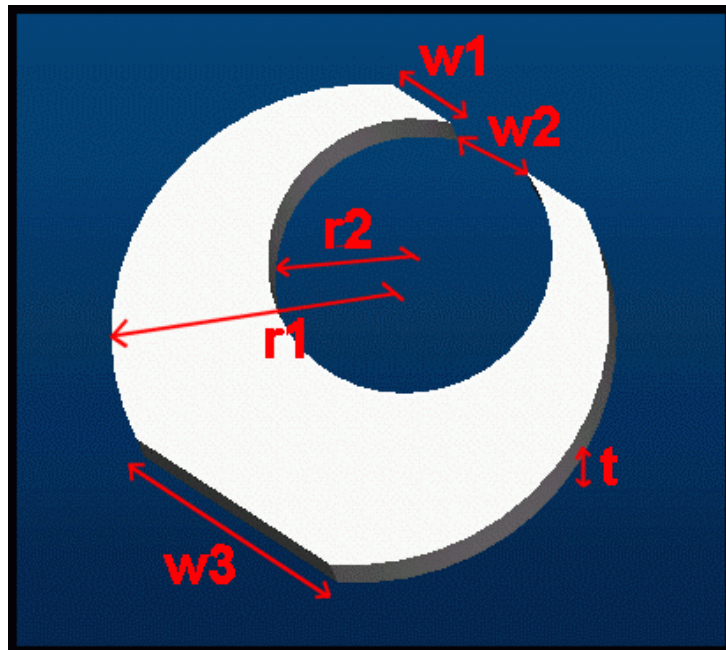iii) $w1 \leq 2 \cdot r2$,　iv) $2.r1 \geq w1 + 2.w2$

Figure D.26 - Crescent Fork

The *Crescent Fork* is a specialized form of primitive element. The explanations are given below:

r1 : diameter of the big Circle

r2 : diameter of the inner Circular Zone cavity

w1 : width of the tip

w2 : width of the Circular Zone cavity

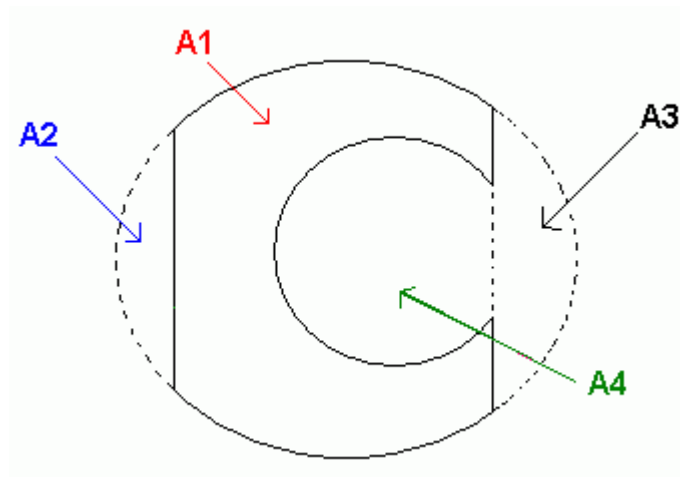**w3** : width of the outer cut Circular Segment

Figure D.27 - Crescent Fork Zone Explanation

The Area fragmentation figure and the formula of each Area is given below:

A1 : The Area of the total Circle

A2 : The Area of the outer left Circular Segment

A3 : The Area of the outer right Circular Segment

A4 : The Area of the Circular Zone

Volume: V = (A1 - A2 - A3 - A4) . t

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$A1 = \Pi \cdot r1^2$

$A2 = (\tfrac{1}{2} \cdot r1^2 \cdot (X_1 - \mathrm{Sin}\, X_1))$

where, $X_1 = 2 \cdot \tan^{-1}[w3 / 2.\sqrt{(r1^2 - W3^2/4)}]$

$A3 = (\tfrac{1}{2} \cdot r1^2 \cdot (X_2 - \mathrm{Sin}\, X_2))$

where, $X_2 = 2 \cdot \tan^{-1}[(w2 + 2.\,w1) / 2.\sqrt{(r1^2 - (w2 + 2.\,w1)^2/4)}]$

$A4 = (\tfrac{1}{2} \cdot r2^2 \cdot (X_3 - \mathrm{Sin}\, X_3))$

where, $X_3 = 2 \cdot \tan^{-1}[(w2) / 2.\sqrt{(r2^2 - w2^2/4)}]$

Limitations: i) $r2 < r1$, ii) $w3 \le 2.\,r1$

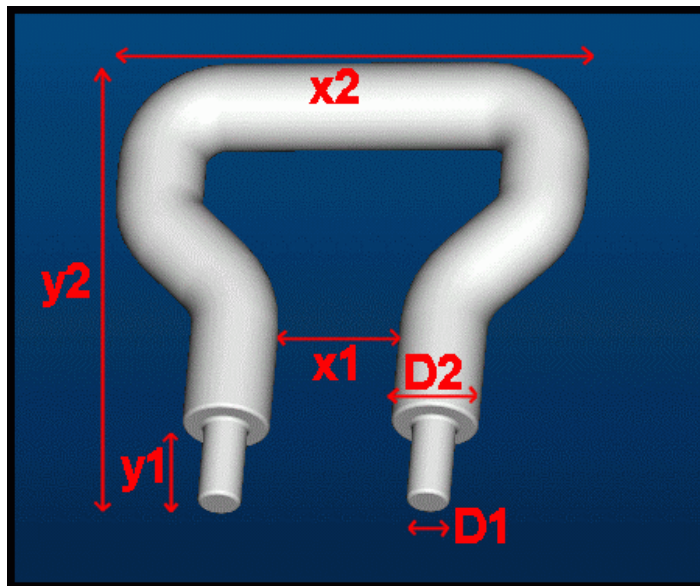iii) $w2 \le 2.\,r2$, iv) $2.r1 \ge w1 + 2.w2$

Figure D.28 - Mapa Fork

The *Mapa Fork* is a specialized form of parametric primitive element. The explanations are given below:

y1 : length of the front Cylinder

D1 : diameter of the front Cylinder

y2 : length of the Mapa Fork

x1 : distance between two Forks

x2 : width of the Mapa Fork

D2 : diameter of the Fork

Volume: $V = (2 \cdot \Pi \cdot D1^2 \cdot y1) / 4 + \Pi \cdot D2^2 \{(x2 - D2) + 2 \cdot (\sqrt{[((x2 - x1) / 2 - D2)^2 + (y2 - y1 - D2/2)^2]}\}$

Limitations: i) $x1 < x2$

      ii) $y1 < y2$

      iii) $D2 + y1 < y2$