Economic control of steel fabricated components at the design stage

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ECONOMIC CONTROL OF STEEL FABRICATED COMPONENTS
AT THE DESIGN STAGE

A Thesis Presented to the Loughborough University of Technology for the Degree of Doctor of Philosophy

by

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M.Sc., MTech.

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Acting Director of the Engineering Design Centre,
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© by I. Shadravan, 1983
To: Shahla, Shabahang and Farhang

To: the memory of Parto and Shohre

To: My parents

To: All those who help without being known
ACKNOWLEDGEMENTS

The author is deeply indebted to Mr S Pugh, Acting Director of the Engineering Design Centre, for his kind advice, help, guidance, enthusiasm and patience during the progress of this research. He managed to bring the work back to life after one year of dormancy.

I also wish to thank Mr D G Smith for his encouragement and help, Mr T Kirk for his help and advice on computers and graphics and Mrs C E Woodiwiss, Secretary, for her typing and editing advice.

I am also extremely grateful to the companies who allowed me to collect data and information from their workshops and planning sections. Namely, Mark (UK) Limited - especially Mr C Henderson for his assistance, Baker Perkins Limited - particularly Mr C Mellor, Pegson Limited, The Marconi Company Limited and British United Shoe Machinery Company Limited.

My special thanks are also due to all those kind people in the fabrication shops for all their advice on the processes.
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SUMMARY

The economic aspects of the design of fabricated components have been analysed and clarified. The parameters affecting fabrication economy have been discussed based on the information available to a designer. The approach to the most effective design parameters has been studied and specified.

An analytical approach to the time consumption of the processes involved has been established based on the standard times available. Costing systems (coarse to fine) for welded fabrication, by either MMA or semi-automatic CO2 welding, using component design parameters have been presented. The differences between the planned times from various companies have been explained and presented as an adaptation factor in the equations. An equation for estimating total operation time for the whole fabrication process, including piece preparation, assembly and welding has been established, its parameters being within the designer's control. An equation for estimating setting times has been introduced and the importance of setting time has been discussed.

In estimating material cost, allowances have been made for material wastage, due to quantity change, nest and gain, scrap losses and the effect of learning improvement. The costing of consumables has also been specified.

A nomograph has been prepared for the estimation of total operation time, reducing significantly the time and effort required. An economic guideline for designers has been introduced to achieve an optimum design.
Introduction

1. The Purpose of Economic Control at the Design Stage

1.1 Design Economy, as a Design Criterion

One of the main criteria in any design work is its economy (25).
In other words a design may never satisfy a need unless the product cost is below a certain value. The value of a design gradually emerges as the design activity proceeds through all its stages.

The first questions that anyone may naturally ask himself whenever he wants to do something are; how long am I supposed to spend on it?, what are the facilities available?, and what kind of effort am I supposed to put in (specialities). Whether one is out walking, building up a new complicated system or solving a purely mathematical problem, the above mentioned questions always come into one's mind and an estimation takes place, either very quickly or over a longer period of time. What is the output of the estimation?, cost, i.e. effort and speciality plus materials and equipment. If the estimation shows that it is beyond one's ability, one would not do the job at all. The estimation may not be accurate, and some times this may create a problem, because it may not always be based on fact or there is no logic behind it.

People are not usually aware of the fact that they are carrying out this type of estimation. It may be done subconsciously and because of that fact, parameters may not have been chosen and used correctly.
Logical following of the stages should be regarded as a designer's duty. Consciously working under a cover of economy should also be generally accepted as a designer's duty. If one does not believe in the fact that every single activity he comes out with is and should be under a cover of economy, he may never be able to find why some of the results of his work are not successful. Underestimating is the problem with most of the unsuccessful design. Let us study the design stages and see how economy works;

1.2 A Designer Controls Economy Through Design Activity

A design starts from a need, which in turn has got an economical face; i.e., the need must be satisfied with minimum cost, which means minimum effort and minimum material. But since one cannot give a value to that minimum cost, one should give a value for the maximum permissible cost. This maximum limit will produce a target cost that a designer must work within. The target cost may be considered as a loose or a tight one depending on the strength of the need. In almost all of the cases it is the designer's task to specify that maximum permissible cost. And if one did mistake on this first evaluation, the final design may not be successful.

The first stage in any design is concerned with the study of the need and the present solutions. The designer will specify a list of the features required for the new device, in the form of a product specification (25). The designer thinks that if a device could be designed to satisfy all the requirements of the specification, then it would be a better solution than the present ones economically.
The next stage is to generate as many concepts as possible, in order to choose the optimum one. Apart from the cost itself as one of the criteria to achieve the optimum choice, simplicity, ease of operation, maintenance, feasibility, size, material, power consumption, or other criteria are all features of the cost, and the designer will evaluate all concepts against the criteria.

The next stage is detail design, material selection, stress analysis and process selection. At this stage a similar approach will be adapted; ie, simple mechanisms, simple components, easy to make, standardised components and so on. But many designers have never asked themselves why these are good features. If they had, the answers would certainly have made them design more consciously.

Stress analysis is carried out for the same purpose; why one prefers to choose an I section rather than a flat bar for a simple beam under a load (see the diagram)\textsuperscript{2}?. Why should one control the section for a loaded member using stress formulas with a specified safety factor.

If one takes a size larger than what was found by stress analysis it is called over design (3). Why has it been suggested to apply "load line approach" in detail design (26)\textsuperscript{2}?

Designers have been advised that "Design should satisfy strength and stiffness requirements" (3). Fig(1-1) shows a
hollow section
one piece

2 channels
hot rolled
2 joints

4 angles
hot rolled
4 joints

2 angles
hot rolled
2 joints

4 plates
4 joints

one plate
3 bends
one joint

2 plates
4 bends
2 joints

4 plates
4 bends
4 joints

2 plates
2 bends
2 joints

2 plates
2 bends
2 joints

non-symmetrical

Figure 1.1: Complexity analysis for the same need.
simple component with a specified configuration, strength and stiffness, but made from different forms and by different detail processes. Only one of these 10 varieties can be the optimum choice for a particular purpose ie, the one which could be produced with minimum cost. Of course, if a rolled hollow section was not available and the component was under a serious fatigue load, then the one with corner joints should be avoided, since it would not satisfy the strength requirements economically.

At the end of a design activity, but before sending it for production the cost of the device is estimated in detail. This is to check whether the manufacturing cost is within the target or not.

Consequently design economy, which is to satisfy a need with a better economy, should be considered consciously during every single stage of design activity.

One may have noticed that this analogy of the economical aspects of design is totally based on the relation between a designer and needs which come from the people, and nothing else. The economy policy of a designer is based on the actual need and how it can be satisfied in a most economic way, to be useful to more people (34). By adapting this policy, the less the product cost the deeper is the relationship between the designer and the consumers. For instance, a wheelbarrow, an electric light, a pencil, a gear train, sand moulds, an arc welding equipment, are in common use throughout the world since
they are economic products and processes.

1.3 **Design Costing is a Designer's Need**

1.3.1 **Techniques to Control Design Economy**

In the last section there was a discussion as to why a designer must and does consciously control the economy of a design. Logical performance of this aim requires some techniques. To do a good design, one may start with planning the activities and put the stages in a particular order and not randomly; what is the first stage and how long should it take, the next stage and so forth. Particular techniques are available for these purposes and may be found in the relevant reference books.

After the first stage one may need tools for market analysis, this is also a technique to specify the actual need in detail, i.e. design specification. Some of the other techniques required by designers are; brainstorming, synthesis, concept evaluation, value analysis, material selection, stress analysis, engineering graphics, costing, etc (27). These techniques are the designer's tools and they should be used to logically establish the final design.

Many tools have been prepared to assist designers, since they have been found to be needed by them. Some of these tools have been modified and rationalised to be made easy to use, but some of them are still unusable and not practical. Very few usable techniques are available to the present time to assist design costing.

Most designers prefer not to use available techniques because
they may be inaccurate, time consuming and not very practical. They usually send a general assembly drawing to a cost estimator or call in a production engineer for help. The result from a cost estimator may be unrealistic and based on his previous experience. Why does a designer not like to carry out costing particularly since he needs the result to control his design? The reason is quite simple, without a proper tool he is incapable of doing it. What he requires is a tool to make costing:

"1- simple, quick and easy to carry out
2- Sufficiently accurate
3- based on factual rather than on comparative costs" (28)

This means a tool for costing that in itself does not cost very much.

There are some guidelines and general graphs on this matter but they are not of much assistance. For a designer to undertake the actual economic control of a design looks like being lost at sea with no sign of the shore. An expert designer may get safely ashore, although not always, but an inexperienced one can only cross his fingers and wait for his chance. Designers have been and always will be asked to design components as simple as possible but we may not know what the minimum limit for that simplicity is if the cost is not known.

A suggestion has been made to designers in heavy engineering (29): "In considering alternative designs, the most important criterion is the cost. In America it is customary to provide a Value Engineer to advise the designer of the
cost of different designs. When a product is completed a post-mortem is held by a committee to recommend modifications for future cost savings."

But this is a trial and error approach which is not logical and may cost a lot of time and money.

Does the value engineer do the costing by using a simple and quick tool? If so, then the designer can do it. But if he just guesses the cost of a design based on his experience, then how reliable is his judgement especially if the value engineer has little or no experience?

1.3.2 Component Costs During Design

Component cost is estimated at the detail design stage for different purposes:

1- To choose the optimum concept.
2- To select the manufacturing process. In relation to this work the question is mainly to decide on either fabrication or casting.
3- As a part of costing of a whole device to see if it matches the specification target cost.
4- To understand the main features and factors affecting the component cost.
5- To find areas of cost concentration in the component and to reduce it.
6- It is a valuable experience for a designer and one may learn a lot about how to design better in the future.
7- To advise the production planner and cost estimator, (perhaps in future a design team with the proper tools
can eliminate the lengthy job of cost estimation being done by the cost estimator at present time).

One must bear in mind the designer’s information available at the time when the cost of a particular component is required. The designer may know, for instance, about the configuration of the component, dimensions, weld sizes, material and the manufacturing processes available. But he certainly may not know, for example, the revolution per minute of a disc saw on the shop floor or the efficiencies of different electrodes required in the welding operation.

1.4 Relationship Between the Designer, Production Engineer and Cost Estimator

Any of these three has got a certain duty in relation to the final economy of a product. A designer’s task was discussed earlier. Information on the available materials and the costs, the machines, equipment and their capabilities as well as processing times in detail, the accuracies that can be easily achieved within the shop, standard sizes and technical comments are some of the necessary feedback from the production engineer and estimator that a designer needs to improve cost estimation at the design stage.

A estimator’s costing approach is and must be different from the designer’s approach. An estimator has to evaluate the raw material in detail in order to prepare the purchasing lists. He estimates the amount and detail of consumables, processing times for different machines, the operation factor of processes
over head, profit, waste and scrap, payments, wages, etc. But a designer just wants to know whether he is working within the design specification or not. And if not where the dark points are located and what the remedies are.

The author appreciates that: "It would be wasteful of design time if the time for every operation were calculated." (32), and even more than that; "It is not the business of the designer to obtain the manufacturing costs, or the wage costs, of individual components." (35). These are other people's specialties. But the author believes that a designer should be able to select the manufacturing process, the optimum component concept, preferred features in a component and the cost. He should know about the whole product cost, feasibility of a design in relation to the manufacturing facility, the best usage of plates and sections, and the processes accuracy.
2.0 WHAT IS METAL FABRICATION

2.1 Definition

Metal fabrication is a term used to cover a variety of constructions formed from metal pieces, plates and rolled or extruded sections which are cut, bent and joined together. It is used to manufacture rough mechanical components, prior to machining, as well as structural components.

Metal arc welding is one of the main permanent joining processes for metal. Metal fabrication with arc welding joints has found its most favourable application with weldable steel and it is this field which is the concern of this present work.

Other terms that are used for this type of component, in literature as well as in industry, are fabricated components, fabrications, welded component, welded construction, welded fabricated structure, weldment (in USA) and so on. It must be noted that there is quite a difference between the use of the term "fabrication" in the American literature and in this country. In the American literature all of the processes used for component manufacture are called fabrication processes (7). Thus casting, forming, forging, machining and the like are known as fabrication processes (7). Fig. (2-1) shows a component that has been manufactured from steel by a fabrication process.

2.2 Applications

Among the main processes being used in industry for component manufacturing, metal fabrication has a wide variety of applica-
tion. It has been used in many cases, especially by designers, as it is the only available manufacturing process for mechanical components. It is because of the versatility of the process and its capability of being used for the manufacture of complex components in wide varieties. The process is also in competition with casting whenever a designer wants to decide on an optimum manufacturing process for component design. This has opened a new field of research, recently, to compare fabrication with casting base on the design criteria and requirements (1,3), although, as Davies has emphasised, economy is always the main criteria, "The relation cost between fabrications and castings is in practice the most significant factor in the choice" (1).
The variety in metal forms as well as equipments and processes available are the significant reasons for the high applicability of this particular process. Cuts, bends, welds, assemblies and handling are being carried out manually as well as semi-automatic or by fully automatic machines with high speed and precision. Therefore if the economy could justify the feasibility of a particular process, any component complexity in shape is practical.

With metal fabrication the designer has the advantage of manipulating the material placement in order to achieve economy. The number of the pieces for a single component may range from two to hundreds of pieces of different shape and size. Steel fabrication has found its application in many fields of machinery industries such as machine tools; shop floor equipment; jigs; mining; agricultural and civil engineering as well as military equipment; food production and baking machines, chemical engineering and pipings; ship building and many other areas.

2.2.1 The Joining Process

In comparison with other joining processes, ie; brazing, soldering, riveting, glueing or nuts and bolts, welding is quite compatible in many aspects such as having good strength, ease of processing, reliability, rigidity, appearance, load distribution, working life and resistance to the effects of the environment. Relatively low cost and simplicity are two other major advantages of this process in comparison with direct competitors, ie; riveting and nuts and bolts (5).
2.3 **Material, Size and Form**

2.3.1 **Material Compositions**

Although *most* metals are capable of being welded in some way, steels, and especially mild steel, is the most weldable material. This work concentrates on the fabrication of mild steel in accordance with BS 4360 1968 which is titled, "Weldable Structural Steels". Steel weldability depends on the chemical compositions that could be welded with no extra process cost, nor use of special electrode and with good quality of joint in normal speed and ease of processing.

Carbon equivalent is the main criterion for mild steel welding, the percentage of which must not be exceeded, especially when the material thickness is more than 30 mm - otherwise preheating or post-heating in cutting as well as welding would become necessary. BS 4360 has given an approximate limit of 0.40% as the maximum carbon equivalent for weldable structural steels. The carbon equivalent should be calculated using the formula:-

\[
\text{C.E.} = C + \frac{\text{Mn}}{6} + \frac{\text{Cr} + \text{Mo} + \text{V}}{5} + \frac{\text{Ni} + \text{Cu}}{15} \quad \ldots \ldots (2-1)
\]

In heavy engineering, maximum permissible carbon equivalent of materials is usually specified in the manufacturing drawings. This is to minimise the possibility of joint defects and any pre-heating requirements. Moreover, a control test to detect defects and laminations may be required to be performed before processing starts. This is common when a component is made of thick plates and subjected to serious dynamic loads. In such cases the quality of joints and the raw material would be critical.
2.3.2 **Classification of material thicknesses**

Metal thickness is classified in five different groups for the purposes of this work.

(i) **Sheets - up to 4 mm thick**

Sheet metal working is a class of manufacturing work which has characteristics of its own, different from metal fabrication and the cutting, forming and joining processes are different. This range of thicknesses has not been considered in this work.

(ii) **Low thickness - 5 to 20 mm thick**

This is the thickness range used for light to medium weight component. Joints with simple square edges, one side or double side welded, and with continuous or intermittent welds are the common features of components in this range. Welds are usually produced in single passes. Large components to carry light loads and having fairly high rigidity are typical of this range. Also in this range, there is more opportunity for using high speed cutting and bending processes (see Sec.2.6).

(iii) **Medium thickness - 20 to 40 mm thick**

This group is used more extensively than any other thickness range. In this group, square edges may not give the required economy and joint strength. Full strength joints are usually edge-prepared and made by multi-pass welds.

(iv) **Thick plates - 40 to 100 mm thick**

The main application of this group and the next group of thicknesses is usually in heavy engineering where the components and joints are subjected to heavy loads.
Pre-heating may be required for cutting and also for welding. If the thickness exceeds 50 mm, more care is required in the choice of edge type and the quality of the edges becomes a critical factor.

(v) Very thick – or larger than 100 mm
This is the thickness range in which the whole process needs special care, accuracy and shop capability in order to produce economic components of high quality and reliability.

In this work the range of material thicknesses which have been studied using the practical data available is covered by groups (ii), (iii) and (iv), i.e. from 5 to 100 mm thick.

2.3.3 Material Choice
All rolled or extruded forms of raw material available such as plates, angles, channels, beams (I, T or H), thin or thick walled hollow sections, flats and the like have been considered.

One of the highest advantages of steel as a raw material is because it is mass produced in a very wide range of forms and sections. In other words, one may say that the good mechanical property of steel, with low cost, has provided so much demand to be mass produced in such a variety.

Proper usage of material forms in a design can reduce the product cost effectively. A designer must be aware of all standard sections and forms available on the market as well as their applications and cost. Plates are the cheapest in comparison with other forms, whilst closed sections are the
most expensive. The cost of open sections lies between these two groups but the differences could be compensated for by the other advantages of sections if they are used properly. Components made of sections can be much lighter than if they were made from plates (4). Also the mechanical properties of different sections are not the same, since the manufacturing processes are different.

2.3.4 Steel Prices
Steel prices do not change very rapidly. Even the relative changes in comparison with the other materials and especially with labour rates are negligible over a long period of time (say one year). Then in a product cost estimation one may consider it as a constant for a period of time.

2.4 Product Quantity (FC) and the Effects
2.4.1 Low to medium batch quantities
Fabrications are usually produced in small to medium batch quantities. The batch quantity is usually less than 50 and in very rare cases may go up to 100 (ref 22 page IHMC). Fabricated components may also be produced continuously and in large quantities. This type of production has not been considered in the present work, the reason being that the FC of a product affects the whole of the manufacturing process as well as the equipment used. In the case of continuous production, highly sophisticated and fully automatic processes become necessary. The design and production planning would be different. So the economic policy and the costing are different as is the layout of the work and the detail of various processes. The processes which are economically suitable for low to medium batch
quantity are not feasible for the other type and vice versa. One is a short term product with an expected demand to restart it and the other is a long term product with a highly predicted demand. Consequently the economic control of two production groups at once, because they are different in so many features, is difficult and not practical.

In Sec.(2.6) the main processes and equipment suitable for small to medium product quantity has been discussed. One may appreciate that the variety of the processes covered by this work is so wide that it does not permit any further consideration of processes involved in the other types of production. Motion and work study is much more feasible in fully mechanised processing (work Study & O & M, glossary BS 3136).

2.4.2 The Effects of Production Quantity

When FQ in a fabrication is not high, the processing equipment in the workshop are of the general purpose kind and they may possibly not be used continuously. Thus the equipment utilisation is low; the relative equipment cost is low and so is their effect on product cost.

In contrast, the processing machines in continuous production are usually mechanised or automatic and their relative costs are much higher than equipment in the other type. Therefore, in order to keep their effects on product cost to a minimum they should be highly utilised, which means they must be kept in continuous use, and this is the main reason that the use of such equipment in low to medium batch production is not economical.
One other reason with a similar effect is the difference between their setting times. The more automatic is the operation of a machine the longer the setting time.

In general, as the product quantity increases, there are many opportunities to reduce the manufacturing costs of the product. The contribution of setting time for every single process decreases with the increase of P/Q (see Sec. 6-11). The product improvement curve (or the learning curve) is a cost reduction factor based on P/Q.

Nest and gain in cutting pieces is another factor affecting economy, as is scrap reduction, which is practised when P/Q is high (see Section 6-12). Of course the attainment of this practical advantage depends on the ability of both the production planner as well as the designer in the way that they adapt the component detail to obtain the most benefit.

Economical usage of multi-torch and/or stack cutting comes into consideration with the increase of batch quantity (see Section 2.6.1.2). Manufacturing aids such as jigs, positioners and handling equipment become more prominent in the reduction of manufacturing costs with increase in P/Q. High P/Q can mean increasingly sophisticated jigs and fixtures as P/Q and low cost will depend more heavily on their usage. All these parameters are (or should be) studied by a designer to achieve optimum economy of a design.

2.4.3 Conclusions
Investment in machines and shop floor equipment in a factory is
affected directly by a product quantity. Therefore, the design and production costs are under the influence of this parameter.

2.5. Standards and Definitions, Units and Symbols

2.5.1 Standards

The standards that have been used in this work are mainly based on the British Standards. A list of relevant British standards are presented in Appendix (A). There are different standards on processes, equipment, consumables, materials, joints, tests, heat treatment, or glossary and terms.

2.5.2 Definitions of terms

The terms that have been used in this work is classified in three different groups:

(i) Standard terms: These are the terms whose definitions are available in the relevant British Standards and especially in B.S. 499 (Part 1). A list of the standard terms that are in common usage and have also been used in this work are as follows;

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<td>3267</td>
<td>Arcing time</td>
<td>3232</td>
<td>Covered electrode</td>
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(ii) Common terms; Terms that have been used in most of the relevant references in UK but have not been found in Glossaries. The definition of the following terms are given in the relevant sections:

1- Assembly (2.6.3)
2- Component material (6.12)
3- Deslagging and cleaning (2.6.6.1)
4- Direct and indirect costs (3.1)
5- Fabrication time (3.2.1)
6- Inspection (2.6.7)
7- Labour cost (3.2)
8- Machine flame cut (2.6.1.2v)
9- Manual flame cut or Hand burn (2.6.1.2 iii iv)
10- Manufacturing cost (3.1)
11- Material cost (3.2.2)
12- Metal fabrication (2.1)
13- Operation time (3.4.3)
14- Overhead cost (3.2.4)
15- Over welding (2.6.3)
16- Piece preparation (2.6)
17- Product Quantity (PQ) (2.4)
18- Running time (3.4.4)
19- Scrap, wastes and defect (3.2.3)
20- Setting time (3.4.2)
21- Set-up and fit-up = To position and accommodate pieces during assembly.
22- Standard time (4.1)
23- Sub-assembly (2.6.3)
(iii) Other terms; These are the terms which have been found, either in a very few references or created for particular purposes in this work. These are especially related to the detail component data that have been collected from companies. Some of them are being used by the people in the companies with which the author has had contact during the course of this work. They could be called professional terms and are defined as follows:

1- Component = A construction made of pieces that are welded together as a unit.
2- Component weight = Total weight of the component at the end of fabrication process.
3- Component pieces = All of the pieces that are welded together to make a particular component.
4- Component items = The variety in shape and/or size of the pieces in a component.
5- Joint variety = Joints in a component that are different with each other but not necessarily in length.
6- Joint complexity = A simple accessible straight line with squared edge is a joint with no complexity.
7- Piece complexity = Complexity in the shape or form of a piece which requires extra process to be produced.
8- Mark out = To transfer dimensions required from the place where they were obtained to the workpiece by the aid of templates. (3)

2.5.3 Units

The units that have been used in this discourse basically
follow the international system of units (SI), but with some adaptation based upon practical usage as follows:

i) Weight $= \text{kg.}$ (weight of material, component or electrode)

ii) Length $= \text{Meter m}$ (used for cutting or joint length)

iii) Thickness $= \text{Millimeter mm}$ (Material thickness and weld size)

iv) Time $= \text{Minutes min}$ (The duration time for processes)

The reason for the choice of this particular unit system is because, in industrial practice, raw material dimensions are given in meter except thickness which is given in millimeter.

The minute has been chosen as the unit of time since in almost all of the relevant literature, manufacturing times are given in minutes and some times in hours. Since processing times, especially in welding, are not usually short periods, the minute was found to be the most practical unit for the purpose.

### 2.5.4 Symbols

The symbols and abbreviations of different terms which have been used in this work are as follows:

- $C = \text{Cost}$
- $C(\text{fab}) = \text{Fabrication cost}$
- $C(M) = \text{Material cost}$
- $C(L) = \text{Labour cost}$
- $C(\text{OH}) = \text{Overhead cost}$
LC = Duty Cycle or Operation factor
DR = Deposition Rate (electrode)
EE = Electrode Efficiency
Fa = Adaptation Factor
Pcb = Piece complexity Factor
Fng = Nest and gain Factor
Fw = Weld Factor
I = Number of items in a component
Icb = Number of items with complexity
l(c) = Cutting length m
l(j) = Joint length m
N = Number of pieces in a component
Ncb = Number of piece complexities
Nj = Number of joints in a component
NDT = Non-destructive test
PQ = Product Quantity
T = Time min
Tc = Cutting time min
Top = Operation time min
Tset = Setting time min
Tw = Welding time min
T = Material thickness mm
Tw = Weld size mm
W = Component weight kg
Wp = Piece weight kg
2.6 Fabrication Processes

A basic knowledge of processes and equipment involved in fabrication is vital for a designer.

The fabrication process, in brief, is a two-stage process, first cutting and then joining. The first stage is called "piece preparation" and the second "assembly and welding". For a fairly complicated component one may, in detail, expect the following processes to be required.

2.6.1 Piece Preparation

2.6.1.1 Mark out

Very little information could be found on this matter in the literature search. Most of the following has been collected directly from visits to the shops of companies concerned with metal fabrications.

Piece dimensions are transferred from a drawing to the work-piece either by setting a machine or by using templates and marking out the pieces manually. Templates are made either of hardboard or thin metal sheets, cut and marked to the detail in full scale. The processes that usually require marking out are oxygen cutting by hand torch, some shearing and bending, hand operated nibbling, punching, assembly with no special jigs and so on. In general manual feeding or adjusting as well as hand operated processes require marking out. A template may also be used in either a semi-automatic oxygen cutting machine or a semi-automatic nibbler. In some of the oxygen cutting machines a full-scale drawing is used as a template.
2.6.1.2 Cutting Process

This is a process with many varieties which depends on the material thickness, shape complexity of the piece, material form and available equipment. As has previously been mentioned, equipment used in a fabrication shop for low to medium batch quantities are mostly general purpose machines. They are usually manual operated or semi-automatic, as follows:

(i) Shearing by Guillotine

Straight line cuts of thin plates <10 mm thick is usually done by shears or guillotines. Compared with the other processes, cutting by shear is a fast process and the setting time is about 15-17 minutes (4). Although both manual and hydraulically operated guillotines are available in a fabrication shop, the manual ones are used either for casual purposes or in sheet metal works (8). Thus only hydraulically operated guillotines would be applicable in the field of this work. It is a cold cutting process and machines are limited in terms of plate thickness and length.

(ii) Sawing

Sections up to medium size and bars are cut off, either by circular disc or hacksaw. Disc saws are more applicable, especially for bigger sections since cutting in other angles than square is possible (10). No complex cuts can be carried out by these equipments, although stack cuts in sections are also possible. Cutting speed is relatively slow but setting time is about 14 minutes.
(4 Chapter 4).

Light sections can be also cut by a cropper but the cut is not accurate since the metal around the cut edges becomes distorted. This process could be used only when accuracy is not of such importance, for stiffeners or when the cut edge is not to be used as a joint edge. Heavy sections and tubes are cut by either hand burn or disc saw.

(iii) Nibbling

Nibbling is used for plates less than 8 mm thick and where the cuts are not straight lines. It is a relatively lengthy process compared with shearing, whilst its setting time is about 8 minutes. The thinner the plate the more applicable is the process.

(iv) Oxygen cutting

Plates of any thickness or shape can be cut by oxygen torch (burning) either manually or on a machine. Oxygen flame cutting is only used for cutting iron or metals of high iron content. Steels with more than 0.3% carbon content need pre-heating. The chemical reaction is:

\[ 3 \text{Fe} + 2 \text{O}_2 = \text{Fe}_3\text{O}_4 \]  

(Ref 4)

which involves a considerable amount of heat. Machine flame cutting is much faster and more accurate than by hand burning.

(v) Cutting by machine:

Oxygen cutting machines are the most applicable for plate cutting. They are used as semi-automatic machines
since the operator must set and adjust the torch, template, the cutting speed and heat the starting point. After that the torch will automatically trace out the shape of the piece by the aid of a tracing device attached to the machine. The device will follow the outline of the model.

One disadvantage of this process is material waste, because there should usually be a gap between piece edges and material edges to minimise a heat distortion. The varieties in piece shapes and thicknesses, cut by using the same machine may also increase material wastage. Long pieces from thin plates may be heat distorted by this process.

(vi) Multitorches:
Oxygen cutting machine is capable of cutting several pieces with the same shape at once. This is done by using multitorches on a machine. This facility could be used only if a PQ could justify the usage for economy reasons. The setting time is much greater than a single torch, whilst the operation time may be reduced to a certain extent by increasing the number of torches (11). Shape complexities should also be studied before process starts, from a material waste point of view.

(vii) Stack cutting:
Some oxygen machines can cut plates up to 600 mm (24") thick or more. A stack of a number of plates could
also be cut at once by this machine. The process may reduce cutting time if a batch quantity is large enough, although extra time is required to fix the plates and tack weld together. Material waste is another point that must not be ignored.

(viii) Nest and gain:

Pieces with the same thickness can be cut from the same plate with a minimum material wastage. The position of the pieces on the plate should be arranged before cutting commences. A model of this arrangement will be used as a multi-template. Then the machine will cut through all pieces cotinuously. This multi-piece arrangement for cutting is called "nest and gain". It is more applicable in an automated manufacturing process (9), and efficiency in this area results from co-operation between the designer and the production engineer. Trying to minimise the thickness variety in a component is a designer's task, whilst a proper "nest and gain" is a production engineer's duty. It requires time to be performed but it will reduce the material waste and setting time. Cost saving by this method is possible only if the batch quantity, the thickness variety and the amount of material savings are properly considered.

(ix) Manual oxygen cutting:

Using an oxygen cutting torch by hand is relatively lengthy process which depends on the operator's skill. The advantages are versatility and short setting time.
All the complex shapes on the sections are cut in this way. Two disadvantages of this process are mark out - which is done manually - and some inaccuracy of cut edges. Since it is manual, the process speed is not controllable and the product quality is low. Work study is also difficult.

(x) Special equipment:

There are some specialised cutting equipment available; one is a circle cutting device which, by the aid of an oxygen cutting torch, can cut circles out of plates to a pre-set radius. Thus no template is required for this purpose. It may be manually operated with a guide or be semi-automatic (2).

There are also standard punching dies available for cutting holes in thin plate and sections. Each shop usually only keeps the dies that have been chosen as the most preferred hole sizes in the products, and the designer should keep to those sizes.

Some companies may use a special oxygen cutting machine to cut complex shapes in tubes, this is a semi-automatic machine and may not be available in all shops.

2.6.1.3 Bending and forming

Plates up to 15 mm thick can be cold bent to different angles by press brakes. It is a one stroke operation with a relatively long setting time - about 30 minutes - and short
operation times, but ring forming and rolling are relatively long processes.

Manual bending or blacksmithing is not used very often unless for unusual bends. The setting time is short but operation is fairly long and the process is difficult to control.

2.6.1.4 Straightening
This process is used to gain accuracy of straightness of fairly large thin pieces after being cut. Plates as well as sections about 1 m long may require this process if the straightness is to be kept within a certain limit. It is done by a machine where a reciprocating ram hammering against the piece which has been fixed in place. The machine and the piece are set manually. No information was found on this type of process in the literature searched but the machine has been found operating in one of the companies visited by the author (see Chapter 5).

2.6.1.5 Edge preparation
Squared edge joints are practical and economical up to a certain material thickness and weld size (see Section 2-7). The most applicable and practical edge type - other than square - are single and double bevelled edges. A bevel angle usually ranges between 15-60 degree (see the diagram), depending on the joint accessability, process economy and the bevelling equipment available, but the most commonly used bevel angle is 45 degree.
As plate thickness increases, the accuracy of the edge prepared becomes more critical. There are several different machines that are used for this purpose: the most common being an oxygen cutting machine (12) and also a bevelling machine (13). The first one is used to make single or double bevels, being carried out by two or three torches fixed on a mobile head. The process is relatively slow but gives fairly accurate results. In contrast, the bevelling machine which is a sort of chipping machine, is faster with no heat effect involved whilst flame cutting is a fusion process. The process on a bevelling machine is carried out after a piece is cut with square edges. Therefore, two cutting processes must be carried out separately and if a double bevel requested, the bevelling operation must be repeated. The bevelling machine has more versatility since bevelling even a tube edge is possible with this equipment.

Although in a cost comparison between the two processes (13), the bevelling machine has been preferred to a flame cutter (with a very big margin of difference), due to the discussion aforementioned one may doubt such a comparison. In general one may say that the practical economy of the process in relation to machine availability makes the choice. A planing machine can be used for edge preparation on straight lines. A designer should know about all these options and their availability on any particular shop floor.
2.6.2 Summary

The choice of a cutting process, in general, depends on the thickness, form of the raw material and the shape complexity of a piece. From the economy point of view, cutting may be classified into four different groups:

(i) Very short operation time with a moderate setting time - eg; shears.
(ii) Fairly short operation time and short setting time - used for simple cuts on sections, eg; saws.
(iii) Moderate operation time and moderate setting time - used for plates, eg; machine oxygen cutting.
(iv) Long operation time with short setting time - eg; manual flame cutting.

All these four classifications are usually available in a workshop, it is the designer's task to consider his design base on the economy of these choices. After the initial cut of a piece, any further operation that requires either re-setting or a new machine is called extra piece preparation process. It may be a new cut, edge preparation, bending, etc which will cause extra cost on a piece. Bear in mind that the manual process is a lengthy and uncontrollable process. Also edge preparation is quite a lengthy process and although a bend may eliminate one joint, it has a long setting time.

2.6.3 Assembly and tack welding
2.6.3.1 Assembly

This is the most complicated part of the whole fabrication process. It may be defined as the manipulation and adjustment of the pieces against each other in a way that makes them ready for tack welding.

As the number of the pieces in a component and the variety increases, this stage becomes more complex. Several sub-assemblies may be required to make the whole process possible. Careful consideration of these sub-assemblies can make the process easier.

Assembly aids may be required to fix the pieces in their positions until the completion of finish welding. These aids are either multi-purpose devices, eg; clamps, vices or magnetic clamps which are in use for general applications, or they are special devices, eg; jigs and fixtures. Special jigs are designed for a particular component assembly.

A bad design may make the assembly and welding difficult or even impractical. A wrong set-up in a design may increase the product cost. The sub-assembly and assembly sequences of any component are created during the detail design. The batch quantity for a particular component is also a major factor in sub-assembly arrangement. Accuracy and joint complexities are also time-consuming. A large amount of handling may be necessary in this operation. Set-up becomes more difficult with increasing piece weights. Sub-assemblies make handling operations easier and also provide accessibility to those...
joints that, after final assembly, may become inaccessible for welding. The setting time at this stage is only the preparation of fixing devices and the understanding of the work, but the whole work will be repeated for every single set. Better aids can reduce this operation to a certain extent.

2.6.3.2 Tack welding

Pieces of a particular component will be tack welded after they are adjusted and fixed into their positions. Tacking or tack welding is welding the joints with a small weld size, 5 - 15 mm in length and at intervals of 150-400 mm (14). Strong fixtures can minimise this operation.

2.6.4 Jigs, Fixtures, Positioners and Handling

2.6.4.1 Jigs

A welding jig (or fixture) positions and hold together the individual pieces of a component for welding. It reduces the time for setting up and welding. It enables welds to be carried out more easily and to a better quality. One important purpose of a jig is to reduce the need for highly skilled workers (15).

Depending on the quantity and complexity of a product, this equipment may vary from multi-purpose devices to complicated special devices. The cost of a multi-purpose jig is negligible, whilst the operation time is relatively high and capability low. When the batch quantity is not high, the cost of a special purpose jig can affect the production costs significantly. Instead, A well-designed jig can reduce the assembly and
welding time considerably. The main feature of a well-designed jig and the type of operation it is capable of may be summarised as follows (15):

A manually operated jig with lever is the cheapest in comparison with either pneumatic, hydraulic or electrically operated jig. Duplication of jigs can reduce costs. Fabrication is the most common process for manufacturing jigs.

2.6.4.2 Positioners

A positioner is a multi-purpose equipment which is used to manipulate a component into a proper position for the welding operation. A positioner, in general, is a table which can be revolved in about three different axes. A component, when clamped to it, can be positioned in the correct angle for different joints in the component. Welding in positions other than flat or horizontal makes the operation more difficult and lengthy and increases the weld consumption, thereby reducing the quality.

Using positioners can reduce handling times as well as welding time quite considerably, especially for heavy and complex components with frequent joints in different positions. Since heavy components cannot be manhandled into different positions, one may accept that economic policy in any company with heavy products will be forced to use this equipment, ie one should expect to find positioners in any heavy product workshop.

It must be noted that in automatic welding, such as submerged arc welding, positioners are different. They move the workpiece
relative to a welding head with a pre-set speed.

2.6.4.3 Handling
Handling is one of the most costly parts of any kind of manufacturing process. Sometimes the handling cost for a particular product may calculate up to 85% of the total manufacturing cost (16).

In the author's opinion, handling, especially in metal fabrication, is not only the displacement of the workpiece, it also includes the fabricator movements as well as his arms, in holding a torch or a welding head, during allowances and idle times but not the running time. A welder has to adjust his position against the workpiece in order to be able to operate properly.

Accuracies and complexities in a component, as well as manual operated processes are the main factors to increase this kind of handling. Instead, facilities, ie; cranes, positioners, jigs, etc can reduce handling costs.

2.6.5 Inspection
After tack welding an assembly and before finish welding of a component begins, an inspection will be carried out. This is to check if all the pieces are in the proper position, and that nothing is missing. Some dimensional control might be necessary as well as the fit-up of the pieces. This may reduce the possibility of corrections and after weld repairs. Another inspection is carried out at the end of finish welding.
2.6.6 Welding

The two main welding processes that being used for this range of batch quantities are Manual Metal Arc welding (MMA) and CO2 Metal Arc welding.

2.6.6.1 Manual Metal Arc welding (MMA)

In this process a covered electrode, usually 450 mm (18") long, is used by an operator to do the welding (BS 499 part 1). The electrode has different cover (BS 639 1975) for different applications. Depending on the quality, size and weld position required not only the electrode covers may be different but also the electrode size, electric current and voltage.

This process is one of the commonest and is used for a wide variety of products and sizes in firms (17), having its own special versatility and simplicity. Although it is a relatively low speed process, for many complex fabrications with poor access joints, it is still the only practical welding process available.

It has a very low operation factor some times down to 10% (18). Some average of 20% has been indicated in ref.6 (paper 19). The control of the weld quality depends totally on the welder skill. Other applications are tack welding, short run joints formed on structures made of sections, and intermittent welds.

Deslagging, cleaning and electrode changing are extra necessaries in MMA welding. Setting time is very short. Almost 12% of the electrode is wasted as stub ends (18).
2.6.6.2 CO2 Metal arc-welding, semi-automatic

In this process a continuous bare wire electrode is used, the arc and molten pool being shielded with carbon dioxide (BS 499 Part 1).

It is a semi-automatic process, in that the operator must adjust and hold the welding head manually but the wire and gas shield are fed automatically.

In comparison with manual metal arc welding, it is faster and easier to operate. The weld quality is much better and the operator's skill has less effect on controlling the operation. The range of electrode diameter is not very wide. The commonest being 1. and 1.2 mm in diameter. No deslagging is required and the electrode waste is negligible. The average of the Operation factor is 40% which is much higher than the MMA welding.

The disadvantages are; Joints not having ease of access cannot be welded. It is not very suitable for a component made of sections or for short runs. The MMA electrode has a wider range in larger diameters than is available with CO2 welding.

Semi-automatic welding is the most efficient method when there is;

a) A sizable quantity of welds over 80 mm in length,

b) heavy multi-pass welds,

c) large volume fabrication of repetitive assemblies, especially where precise fit-up is impractical.
2.6.6.3 Discussion

Welding is carried out either in a factory fabrication shop or in site. In civil engineering and some very heavy engineering such as in ship building usually welding is carried out on site. But in industry generally it is done in the shop, where handling and manipulating aids are available to reduce the work required in the manner that has been discussed previously.

Welding has been found to be the major part of a fabrication work. In MMA and CO2 welding processes the variety of electrode covers and diameters, voltages, currents and equipments has opened up a wide spectrum of choice for manufacturers. As an evidence of this declaration one may refer to 173 tables and some other informations collected in ref.(19), but this is only a part of the story; For a larger weld size the choice of the electrode and process for tack weld, first runs and the other runs the variety of the tables will become even greater. Accuracy, load features and application of a component may also create another variable not only in the design but in the manufacturing choice.

A joint should be inspected while it is being welded. Joints may be welded either continuously, at intervals or in sequence. Intermittent welds may be used for two different purposes. One is to reduce the welding cost for long joints where the strength is not important and the other is to minimize a heat distortion in long joints of thin plates.

Electrode efficiency EE, Operation factor or duty cycle DC,
deposition rate DR and arcing time are four major factors affecting welding economy. They are inter-related to each other and are shop features for any particular company.

2.6.6.4 Weld defects and the repair
Repairability is one of the advantages of the welding process, in that a welded joint can be repaired if the requirement was not yet satisfied. Some faults are harmless to any component such as over welding or accurate and deep penetrated welds where they are not required. They do not create any weakness or undesirable feature in the component, but just increase welding cost. Over welding could be produced either by a designer, giving the wrong weld size, or by an operator, putting extra weld on a joint.

Joint defects are either internal or surface. Surface defects are much easier to recognize and repair. Under cut is one of the most common joint defects which can be recognized by visual inspection.

2.6.6.5 Preheating
A joint may require to be preheated if the parent materials are too thick or the thicknesses are very different and/or if the carbon content in a material is high (23). Welding should not be undertaken when the temperature is lower than 0 C (BS 1856: 1964). Joints are preheated to reduce the possibilities of weld cracks and also the need to heat treatment. Preheating temperature for mild steel does not usually exceed 150 C. Oxygen cutting of thick plates may also require preheating.
2.6.7 Inspection

2.6.7.1 General inspection

Any visual control and checking of a component is called inspection. When welding in a component has finished, the product will be inspected for two different reasons, ie firstly, dimensional control of the product to see if it follows the dimensions in the drawings, secondly, weld size control. These two may be started from the very beginning of the welding process and continued right through to the end.

2.6.7.2 Accuracy

Dimensional control of a component originally depends on the accuracy required. If at the end of the fabrication process the accuracy was not satisfied yet, an extra machining is needed. This will increase the labour cost and possibly material waste. Inaccuracies may occur during any stage of the processes previously explained.

Accuracy in products are being specified based on the economy (ref. 2 page 46), ie for any manufacturing cost limit certain limit of inaccuracy is acceptable. This relation will affect the decision on whether to maintain a particular accuracy during the fabrication process or produce it by machining afterwards.

2.6.7.3 Pre-fabrication machining

It is often advantageous to perform some machining on components prior to assembly (24). In most of the cases such operations
will increase the fabrication accuracy, and it is feasible if the economy of the design, based on the shop facility justifies it.

2.6.7.4 Joint inspection

Visual inspection of a weld is the most simple control of the quality. A further step is to apply a dye penetrant method (2). To choose a most suitable and economical weld inspection for a particular design, a method of classification of weld qualities can be applicable. Weld qualities are classified in three different groups, i.e., non-critical welds, semi-critical welds and critical welds (20). Any misjudgement on a weld quality may lead either to an unnecessary costly inspection or to a failure of a product in use.

A component with non-critical welds may not require any special inspection. At most, general observation of weld surfaces should be requested. Since the joint does not transfer any significant stress, the chance for a weld failure is remote. In practice they are usually over welded.

Semi-critical welds are usually under moderate loads, considering the weld sizes and lengths. Failure may cause only financial loss. The weld should be checked by a dye penetrant method at least. The method is used to find all surface faults, i.e., surface cracks, craters, spatters, under cuts, over welds etc.

2.6.8. Tests

Weld tests are to qualify the mechanical property of a weld. They are classified in two groups:
a) Non-destructive test (NDT) and b) Destructive test.
In the first group three methods are distinguished;
1- Radiographic test, 2- Ultrasonic test & 3-Magnetic test

A component with critical welds must be controlled at least by one of these processes (20). Internal defects should be repaired if the failure could be hazardous. The possibility of joint defect increases as the weld size increases.

Destructive tests are to control the quality of the welding process, a test specimen being taken.

2.6.9 Heat treatment
A joint may be required to be heat treated when the weld size increases. Since welding is a fusion process, it changes the material structure in the weld zone and because the weld is not cooled evenly it creates residual stresses in the weld zone. Depending on the class of a weld, specified in section 2.6.7.4, heat treatment is another quality control to make a weld meet the properties needed. Stress relieving of a weld is necessary when it is a critical weld, otherwise it could be ignored.

Steels with higher carbon content are more likely to need heat treatment. Proper cooling control and electrode choice can reduce the need to a minimum. But the one that mostly can reduce heat treatment cost is the component design itself.

Stress relieve temperature is recommended to be about 550 C for one to four hours, depending on the percentage of stress to be
relieved, ie 40% to 90% (ref.4 page 4-58). This is the last stage of the fabrication process.

2.6.10 Summary

Metal fabrication is a multi-process production. To produce a particular component, materials with different thicknesses and forms may pass through a combination of different cutting, bending and forming, sub-assemblies and assembly, welding and quality control processes.

Apart from the machines directly related to the processes, many other aiding equipment may be required and some of them must be designed and manufactured for special purposes.

The processes involved have individual application and special characteristics of time consumption for the setting and operation. The choice of some of the processes depends on the product quantity. A fabrication component has several different quality and accuracy features which are limited by the product economy. A designer should be aware of these limitations.
2.7 Joint Design

2.7.1 Joint and weld differentiation

According to BS 499 Part 1, generally there are six different groups of weld joints, i.e. Butt, Tee, Corner, Cruciform, Lap and Edge joints. Within each group there is much variety depending upon the edge type; i.e. square, single side bevelled, double side bevelled, or other shapes.

Among these above mentioned groups butt joints have very little application in mechanical components, rather one may find its applications in chemical industries, e.g.; pipe lines, pressure vessels, tanks, etc., or in ship buildings and so on. Lap joints and edge joints are common to sheet metal works. Therefore it was decided to limit this study mainly to the three other types of joint, i.e.; Tee, corner, and cruciform in that they have found applications mostly in the production of mechanical components.

There are two main types of weld, i.e.; butt and fillet. If the edges of parent pieces are squared and a weld locates between two perpendicular surfaces then it is called fillet weld otherwise it is usually called butt weld.

The following table and the figures represents 12 samples of joints and weld types adapted from 36 figures in BS 499 part 1. These are representative of the joints in most common use.
<table>
<thead>
<tr>
<th>No.</th>
<th>Sketch</th>
<th>Joint type</th>
<th>Weld type</th>
<th>Preparation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td><img src="image1.png" alt="Sketch" /></td>
<td>Butt</td>
<td>Butt</td>
<td>Close square</td>
</tr>
<tr>
<td>2</td>
<td><img src="image2.png" alt="Sketch" /></td>
<td>Butt</td>
<td>Butt</td>
<td>Single-V</td>
</tr>
<tr>
<td>3</td>
<td><img src="image3.png" alt="Sketch" /></td>
<td>Butt</td>
<td>Fillet</td>
<td>Close square</td>
</tr>
<tr>
<td>4</td>
<td><img src="image4.png" alt="Sketch" /></td>
<td>T</td>
<td>Butt</td>
<td>Single-bevel</td>
</tr>
<tr>
<td>5</td>
<td><img src="image5.png" alt="Sketch" /></td>
<td>T</td>
<td>Fillet</td>
<td>Close square</td>
</tr>
<tr>
<td>6</td>
<td><img src="image6.png" alt="Sketch" /></td>
<td>T</td>
<td>Butt</td>
<td>Double-bevel</td>
</tr>
<tr>
<td>7</td>
<td><img src="image7.png" alt="Sketch" /></td>
<td>T</td>
<td>Butt</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td><img src="image8.png" alt="Sketch" /></td>
<td>T</td>
<td>Fillet</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td><img src="image9.png" alt="Sketch" /></td>
<td>Cruciform</td>
<td>Fillet</td>
<td>Close square</td>
</tr>
<tr>
<td>10</td>
<td><img src="image10.png" alt="Sketch" /></td>
<td>Corner</td>
<td>Butt</td>
<td>Single-bevel</td>
</tr>
<tr>
<td>11</td>
<td><img src="image11.png" alt="Sketch" /></td>
<td>Corner</td>
<td>Fillet</td>
<td>square edge</td>
</tr>
<tr>
<td>12</td>
<td><img src="image12.png" alt="Sketch" /></td>
<td>Lap</td>
<td>Fillet</td>
<td>Hole in one plate</td>
</tr>
</tbody>
</table>
2.7.2 **Joint Design**
Choosing proper joints to connect two or more pieces together for a specified requirement may be called joint design. Although many factors may affect the choice, optimum economy within a shop facility is the most important one. In order to achieve this criterion a designer has to consider parameters such as subassemblies, set-up, fit-up, processes, aiding equipments, and thicknesses. Moreover load type, load application and the other component features are to be satisfied by the design (ref.4 page 4-47 to 4-56). Some of the joints are preferred for transferring loads in a particular direction.

Ease of positioning is one desirable joint feature. Joint accessibility for welding should be always considered in the design.

Some joints take longer to be either prepared or welded. Edge preparation of single and double J joints need special machining process that most of the companies in this consideration do not possess. They do not do it even if the thicknesses fall in the range of the application of these joint types suggested by references.

2.7.3 **Joint position**
It has been assumed that components are being welded in either flat or horizontal position (Sec.2.6.4.2). Some of the welding processes are not possible to carried out unless in flat position, e.g; sub-merged arc welding. In practice both manual
and CO2 semi-automatic welding are possible in all positions but with difficulties in overhead and vertical positions. Standard data for welding in different position (19) shows that in comparison with horizontal or flat position, the time for welding in vertical and/or overhead may increase by 300%, whilst weld quality also reduce significantly and large diameter electrodes are not applicable (6).

Over welding may be expected in all welding positions. This is because a weld can never be produced having a flat surface. In stress calculations the minimum size of the weld is taken as the weld size. The undesirable part of a weld is called over weld (see the diagram). A minimum over weld of 10% can be produced in a flat position (21).

![Diagram of Over Weld](attachment:over_weld_diagram.png)

It is not only the gravitational force that helps the flatness of a weld but also the welder has much more control and comfort whilst welding. Longitudinal profile of a weld can not also be a straight line for the same reasons.

2.8 Consumables

2.8.1 Stick Electrode for Manual Metal Arc welding (MMA)

This type of electrode is made of steel wire coated with different protective material which during the welding
operation will be melted and cover the weld. The cover is then called slag and will be removed at the end of each run.

There are many different electrode type for different welding application and these have been classified in BS 639: 1975.

Stick electrodes are produced in a large range of sizes. Four main classes of electrodes are being used with weldable steel. They are called by their type of coatings as: Cellulosic, Rutile, Rutile iron powder, and Basic hydrogen control electrode. Each of these classes with their sub-classes have different applications depending on the requirements. Some of them are good for fast welding with low quality, eg; Cellulosic. Some others are used for special quality of weld such as strength, deep penetration or surface. High deposition rate, ease of deslagging, ease of performance, position, less under-cut and the cost are the special features for some other sub-classes of electrodes. There are even particular electrodes which are good for the first runs of thick welds. Generally, Rutile is used for common fabrication works, whilst Rutile iron powder has a high deposition rate in flat and horizontal position, and Basic hydrogen controlled electrodes are used for good quality of weld against defects (19).

In many companies it is common that the designer specifies the electrode type required in the design, especially when a particular quality is desired for the joints.
2.8.2 Solid wire and Flux cored wire

These are the only classes of electrodes used in semi-automatic CO2 welding. Solid wire with CO2 gas shield is the most applicable electrode in metal fabrication particularly under factory condition. It is a continuous steel wire which is fed automatically during the welding. The range of sizes are .8, 1, 1.2, 1.6, 2.4, 3.2 mm in diameter. This is a disadvantage for this type of welding since the maximum weld size which could be performed, by the range of the electrode available, in one run with normal speed is lower than in MMA welding.

Flux cored wire with CO2 gas shield is used for special condition mainly in welding on site where high quality and reliability of weld is expected within such environments. This type of wire is seldom used in factory condition, since the welding speed is relatively low.
3.0 COSTING and ECONOMY

3.1 Product Cost, Manufacturing Cost

The structure of the product cost has been introduced in references with different classification of the detail. For instance in ref. (30) it is given as follows:–

\[
\text{Product Cost} = \text{Manufacturing Cost} + \text{General Cost (Or Overhead)}
\]

Where:

\[
\text{Manufacturing Cost} = \text{Direct Cost} + \text{Indirect Cost} + \text{Fixed Cost}
\]

and where:

\[
\text{Direct Cost} = \text{Cost of (Material + Labour + Energy + Other)}
\]

and this classification has gone to a detail of fifty different items.

But in ref. (31) manufacturing cost has been broken down as follows:

\[
\text{Manufacturing Cost} = \text{Cost of (Labour + Material + Overhead)}
\]

Where:

\[
\text{Labour Cost} = \text{Direct} + \text{Indirect} + \text{Overhead}
\]

\[
\text{Material Cost} = \text{Direct} + \text{Indirect} + \text{Overhead}
\]

One may get more even confused when he goes through the detail of these classifications. The only practical classification of manufacturing cost, common to both references (35) as well as
the companies that have been in contact with, is as follows:-

\[ \text{Manufacturing Cost} = \text{Labour Cost} + \text{Material Cost} + \text{Overhead} \]

where the Labour Cost is actually a direct labour cost and the Material cost is direct material cost. The rest of the costs are included in the Overhead, ie; indirect labour costs, indirect material costs, general handling costs, equipment costs, material and labour overhead, as well as; rents, buildings, depreciations, insurance, power and heating fuel, taxes, and so on.

3.1.1 **Labour Cost or direct labour cost**

It is defined as the cost of productive labour-works. It is attributable to all those activities which are somehow directly related to a production process and concern the work being done by machine operators, assemblers, welders and the like.

The activities could be either during a change in the form of a piece or a component, or during preparation periods, ie; handling, adjusting and setting of a piecework or a machine.

3.1.2 **Material or direct material**

This refers to the materials that become a part of the product. Some companies do not consider scrap, waste or defects in this category, rather they consider them as an increasing factor in overhead and it is fixed for all of the products in a shop.

For metal fabrication in particular, since welding electrode or
wires would become a part of the component they may be included in this category.

3.1.3 Scrap, Waste, and Defect

Scrap in fabrication is the wasted material that during a process (usually cutting process) is being separated from a required shape out of raw material. It is just a waste of raw material. It is estimated that 75% of the original value per unit cost of material is lost when it becomes scrap\(^{14}\).

But a defect is a product that has lost the requirement during a particular process because of some mistakes. Therefore it is a waste of material as well as work. In metal fabrication this might happen mainly during cutting process, especially if it is being done manually. Welding defects are repairable if required.

The amount of product defects and scrap are studied based on learning improvement (see Sec. 6.13.3).

3.1.4 Manufacturing Overhead Cost

Items included in overhead cost are usually fixed costs for a shop. Overhead is considered as a percentage of labour and material costs. It depends on many parameters such as: Company size, equipments, general accuracy, batch quantity, economy policy of the company, the type of products, labour services, type of payment, etc. This overhead percentage is not the same for all companies. Therefore overhead cost is a cost item that cannot be integrated into a general cost estimation, since it
is company dependent.

The manufacturing overhead is different with the general overhead in a company which is related to administration and distribution costs.

3.2 Fabrication Costs

Fabrication costs can be broken down into the following detail:

\[ C_{(fab)} = C(L) + C(M) + C(\text{el}) + C(OH) + C(p \& fu) \ldots (3-1) \]

Where:
- \( C(L) \) = Labour Cost
- \( C(M) \) = Material Cost
- \( C(\text{el}) \) = Cost of electrode or consumables
- \( C(OH) \) = Overhead Cost
- \( C(p \& fu) \) = Cost Of power and fuel

The labour cost which is the productive labour cost is estimated as follows:

\[ C(L) = \text{Man hours} \times \text{Labour rate per hour} \]

The cost of raw material is the component material cost including the scrap, ie;

\[ C(M) = [\text{Component weight(kg)} + \text{Scrap(Kg)}] \times \text{Material Cost per kg.} \]

Consumable costs is the total cost of electrode or wire
consumed in the welding of a component, including stub ends and spatters, ie:

\[ C(\text{el}) = (\text{Electrode weight}) \times \text{cost of electrode per kg}. \]

Cost of power is the cost of electricity consumed by machines during manufacturing process of a component. This is mainly related to the power consumed in welding process. For all fusion welding processes deposition of steel, a good approximation is to assume 3.85 kW/h/kg of steel weld deposit is required \((18)\). Electricity and equipment constitute no more than 8% of actual welding costs \((6)\).

The cost of fuel is related to the flame cutting process. Typically this is given to be 5.6 m\(^3\)/h or about 12% of cutting labour cost \((33)\).

Overhead costs are usually considered as a percentage of labour cost. In practice it is also common to include the power cost and fuel cost \(C(p\&fu)\) as a part of the manufacturing overhead since they are being considered per hour. Therefore once again the total fabrication cost can be expressed as;

\[ C(\text{fab}) = C(M) + C(L) \times F(\text{OH}) + C(\text{el}) \] ...........................(3-2)

Where; \(F(\text{OH})\) = Overhead cost-factor,

Thus we establish the total manufacturing cost as follows;

\[ C(\text{fab}) = [W + W(s)] \times Cm + T(\text{fab}) \times F(\text{OH}) \times C1 + W(\text{el}) \times Cel \]

............................................................... (3-3)
where:

\[ W = \text{component weight} \quad \text{kg} \]

\[ W(s) = \text{Scrap weight} \quad \text{kg} \]

\[ T(\text{fab}) = \text{Fabrication time of component} \quad \text{hour or minutes} \]

\[ W(\text{el}) = \text{Electrode weight consumed for welding} \quad \text{kg} \]

\[ C_m = \text{Material cost/ unit weight or Material Rate} \quad \text{/kg} \]

\[ C_l = \text{Labour cost per hour or Labour Rate} \quad \text{/h} \]

\[ C_e = \text{Electrode cost per unit weight or Electrode Rate} \quad \text{/Kg} \]

### 3.2.1 Fabrication time

This is the whole productive time that a component may take to be produced and it is the sum of the all processing times. Refering to all different processes involved in fabricating a component (Section 2.6), one may break down the fabrication time in to detail as follows:

\[ T(\text{fab}) = T_m + T_c + T_a + T_w + T_t + T_h + T_b \]

Where:

\[ T_m = \text{Mark out time} \quad \text{min} \]
\[ T_c = \text{Cutting time (including edge preparation)} \quad \text{min} \]
\[ T_b = \text{Bending time} \quad \text{min} \]
\[ T_a = \text{Assembly time} \quad \text{min} \]
\[ T_w = \text{Welding time} \quad \text{min} \]
\[ T_t = \text{Testing time} \quad \text{min} \]
\[ T_h = \text{Heat treatment time} \quad \text{min} \]

On the other hand the processing time for every single operation consists of two parts, i.e; setting time and operation time.
3.2.2 Setting time

Setting time is the time an operator spends preparing for a particular process and the time will be incurred only once for each batch.

A setting time includes all of the times consumed, from the moment the operator is informed to do a job until he starts to repeat the operation for the quantity requested. The time he spends to check the first product and the time for tear down and clean-up, when whole batch is finished, are included in the setting time. Therefore setting time is a value of some importance when a process batch quantity is low.

3.2.3 Operation time

The productive time that an operator spends to do a predetermined change on the configuration of a piece or a component is called an operation time. Thus the times for all of the operator activities that are repeated for every single operation within a batch quantity is operation time, no matter whether it is machine running time, handling, adjustment or any other ancillaries.

3.2.4 Running time

The time during which a change on the material is taking place called running time. In some of the processes running time is relatively very short, eg; cutting by guillotine, press brake bending or assembly. In these processes the operation time mainly consists of time spent on handling, set up, feeding material and adjustments. But in some other processes, eg;
welding or flame cutting, running times are much longer and therefore much significant, and constitute the major part of the operation time. In welding process the running time is called "Arcing time", and deslagging, electrode changing, cleaning, interruptions are some of the ancillary times, especially in manual welding.

3.2.5 Jigs and Fixture Cost

The cost of special jigs are considered as a part of manufacturing overhead cost, since they are being designed and manufactured for the whole life of a production. Their complexity and accuracy, ie; their costs, depend on the need and the batch quantity. If the batch quantity is high and will be repeated for a considerable duration, then the economy policy of the company will permit more investment on special jigs and vice versa.
4.0 ANALYSIS OF PRESENT SOLUTIONS

4.1 Basic Information Available

Very little basic and reliable information could be found in literature on the detail of fabrication processes. Information which is given in catalogues and handbooks is on the working capacities of machines. Cutting speeds of different machines such as flame cutting machine (11 Section 6.1.), motion and work study (66), material forms and costs (36) were found to be more useful for further study in this work.

Information prepared by research institutes such as standard data on welding, operation time, currents, voltages, arc time, deposition rate (D.R.), electrode efficiencies (E.E.), could be found in (19), general process application in (23), calculations of weld sections (3), and they are assumed to be accurate and reliable.

4.2 Costing of Manufacturing Processes

In industry the cost of manufacturing processes is estimated mainly in two different ways. The first is to predict the cost of a product which has not yet been produced and secondly to estimate the cost of a product during the processing period or after it has been manufactured. In this second condition the costing is based on a general work measurement and the experience of the estimator. Since this type of costing cannot be applied during the design stage, there is no point in further discussions.

The prediction of the manufacturing cost of a design is one of the
designer's needs (28). Five different methods have been found in the literature search. These are: unit cost, ratio cost (37), standard cost (39), relative cost (38) and the cost which is being estimated by using a regression analysis technique (40). All of these costing methods utilise cost information that has been collected from the costs of present products.

4.2.1 Unit Costs

In this method the manufacturing cost of a product is predicted by using the unit cost of the product. This unit cost is chosen based on the main character of a product, e.g. volume, length, area, weight, output, capacity, horsepower and the like.

The unit cost method is satisfactory only for a quick estimation where very little information is available. Greater accuracy can be achieved by using separate factors for different cost items (37).

4.2.2 Ratio Cost

The ratio cost factor method is based on the idea that if certain costs of a product are known, other costs, including the overall cost of the product, can be estimated by applying cost factors to the known costs (37).

This method has been used by Rondeau (41) to estimate manufacturing cost and selling price of a product, based on the material cost. Rondeau states that "the cost of materials in a product is the basis for all subsequent cost estimation". He gives the following equation
for material cost estimation:

\[ C_M = 1.2 W \times M \]

where \( C_M \) = component material cost, \( W \) = weight of component, 
\( M \) = raw material cost per unit weight.

The value 1.2 is a factor to take the material wastage into account.

He then postulates that the usual manufacturing cost for a component \( C_G \) is three times the material cost i.e.

\[ C_G = 3 C_M \]

and \( P_s = 3 C_G = 9 C_M \) where \( P_s \) is selling price.

He appreciates that there are logical deviations from the 1-3-9 rule.

4.2.3. Standard Costing

In this technique the analyst defines the actual or desired time, material and burden content for a "typical" or "standard" set of conditions. He establishes this basic standard and compares the actual data with it. The difference between the standard and the actual is the "variance" or deviation from expectations (39).

This method has found a noticeable application in cost estimation since it has got the versatility of usage. An estimator can adjust the standard cost against his condition until he gets the best result. The standard cost can be established with as much accuracy as is required, by introducing more variables to it. As for any other method, care must be taken in the proper choice of variables for a standard cost.

This method has been used for welding cost estimation (See Section 4.3.5.2).
4.2.4 Relative Cost

An adaptation of the approach introduced by Zummerman (38) in 1961, 1962 and 1973, could be represented as follows:

To estimate the cost of a component of given datum from the known cost of a component of different datum, a factor is often used. This simple relation is expressed by the equation:

\[ C_2 = C_1 \left( \frac{V_2}{V_1} \right)^f \]

where

- \( C_1 \) = known cost of product of variable (datum) \( V_1 \)
- \( C_2 \) = desired cost of product of variable (datum) \( V_2 \)
- \( f \) = cost factor

The cost factor, \( f \), may have a value between 0.2 to 1 depending on the type of component and the effect of the variable \( V \) on the cost.

This method is similar to the first method (unit cost) while a general cost chart, similar to that produced by Zummerman (42), could be prepared for any particular purpose and a comparative cost estimate between two products from the same company is possible. Of course the use of this costing method for those products with wide variety such as in metal fabrication seems impractical. This method has found its application in the costing of chemical engineering equipment. The accuracy of estimation depends firstly on the similarity of the two products having their costs compared and, secondly, on the accuracy of a cost factor. Personal experience could affect the choice of similarities.
4.2.5. Regression Techniques in Cost Analysis

This technique can be used as an aid to any of the four methods above mentioned as well as an individual method to predict the cost of similar components. In this approach the estimator tries to find a relation between a group of samples with similarities. He must first consider the actual variables that affect a change in the cost data.

In general this technique is used to find a correlation between two or more conditions variables by taking samples based on every single variable while the other conditions of all the samples in the data are kept constant. After that a method of curve fitting based on the variables will end up as an equation between a dependent variable and the independent variables. This equation will represent the relation between samples in the data.

Regression analysis is a pure mathematical technique so that one must have enough knowledge and understanding of the samples and the variables in the data before applying it. So under certain conditions this method could be applied in cost estimations.

Sometimes, as in cost estimations, it is not practical to provide a data base containing every possible independent variable separately. A study of the data becomes more difficult. An analyst starts with plotting graphs of a dependent variable against independent variables of all the samples in the data, and analyses the graphs trying to find a correlation between the variables. He then chooses an equation assuming that the data can be represented by either a linear equation or a curvilinear
equation such as exponential, polynomial, single variable or multi
variables, and so on. By means of "least square" and other
mathematical tools, the constant values of the equation could be

calculated.

Only within the range covered by the data in a sample can an estimating
equation of this type be used with confidence. But merely because a
given equation can reproduce a certain relation is no proof that it
really represents the nature of the relation. To establish this, we
need a logical explanation which leads to the given equation, which in
turn does closely fit the central tendency of the data. The "true
relation" between the variables may be so involved that a very complex
mathematical expression would be required to represent it properly (43).

For a curve to have real meaning it must be consistent with a careful
logical analysis, no matter whether the curve is obtained mathematically
or freehand. It is particularly to be noted that determination of the
relationship gives no basis for estimating beyond the limits of the
values of the independent variable. Recent resorting to the use of
computers in cost estimation has made the regression analysis to be
welcomed, as an easy technique, by estimators (44). But unfortunately
most of them are much more concerned with the ease of the technique,
rather than being concerned about the logical explanation of the
variables and the accuracy of the results. In respect of metal
fabrication, Thompson in 1956 suggested and used this technique as a
statistical method to forecast the labour cost of arc weldings (45 & 46).

This will be discussed in the next section.
4.3. Metal Fabrication Costing

4.3.1. General Consideration

There is very little material available on fabrication economy or its costing in the literature as such. In almost all of them, one may find some work on welding economy or costs. No one has considered the economy of fabricated components as a whole but one, Pugh (56), who has produced a general graphical guide line on this matter to help designers in their work. This one will be discussed in section 4.4.2. Unfortunately, none of the people working in the field of welding economy have ever considered the problem from a designer's viewpoint. Only those who have given a general overview of welding economy have put a glance at a designer's need. Many of them have never been involved in design work. They have been much more concerned about cost estimators, although not very successfully in the author's opinion.

Generally, the material in this field can be categorised in four groups:

1) Economic aspects of welding
2) Graphical guides
3) Equation for welding cost estimation
4) Computer aided welding costs.

4.3.2. Material Cutting Costs

Apart from welding, one may find some graphical help on labour time for cutting and forming processes in (4). Though not recent information, it is quite reasonable and fairly practical and usable by both designers and production engineers. In addition, the relation between raw material
forms and proper choice of different cutting processes has been tabulated in a useful arrangement. This reference is the only source available giving direct economical information on cutting processes.

The graphs need some modification to aid rationalisation, and this will be discussed in Chapter 6.

4.3.3. Economic Aspects of Welding

Duty cycle for different welding processes, electrode choice and the efficiencies, deposition rates, welding positions, current, voltage and the application of welding processes are some of the aspects that have been discussed in almost all of the literature available. There are also some comments on joint economy but very little about the design (62).

4.3.4. Tables and Graphical Guides

Although T joints, corner joints and cruciform joints have the most applications in comparison with butt joints and the others, researchers have been much more concerned about butt joints. One may argue that it is because butt joints have wide application in chemical engineering and shipbuilding, and most of the welding cost studies have been done in these two areas.

The majority of the information on welding time has been produced by the British Welding Institute (19). In this "Standard Data for Arc Welding", values of arc times and deslagging times, per unit length of weld, have been collected in a set of 173 tables. The tables represent the times for fillet welds as well as butt welds (joints) in
a range of 3 to 25mm weld size both in MMA and in CO2 welding with solid wire. All practical positions, currents, electrode sizes and other parameters affecting a welding time have been recorded. But there is no information for assembly and/or handling time. In a contact with the people in the B.W.I. it was said that since the handling, assembly and tacking time is very complicated and requires so many parameters to be considered, it was not possible to produce any general information on this matter. One may be surprised that the information has covered such a vast variety of parameters in welding whilst there is no practical application for many of them. The values of welding times in the tables above mentioned have been studied in Chapter 6.

Labour times or costs per unit length or unit weight of weld against either D.R., fillet sizes, D.C., plate thicknesses or currents have been graphically produced in (2, 3, 6 paper 4 & 15, 14, 18, 55). There are also graphs on D.R. against currents, and weld weight per unit length of weld against fillet sizes (55) in these references as well as in (19).

One cannot help but notice that the labour costs per unit length of a joint are not really a practical aid, at least to a designer. Because calculating actual weld length of a fabricated component is not easily carried out in a short time. The other graphs are considered even more impractical because the times or costs are given against parameters such as currents, D.R. or the likes. A designer will never have access to such parameters at the design stage and one may doubt whether
estimators could manage with such as these parameters.

In 1949 Churchill & Austin (61) produced a planning sheet as a sample of cost estimations for welded components, but with no detail on welding costs.

4.3.5. Welding Cost Equation

4.3.5.1. Welding Cost Equations in UK

The most efforts that have been put on welding costs in this country are by Thompson since 1955 (2, 45 to 51), Doherty since 1968 (53 & 54) and McMahon since 1970 (6 Paper 4 and 18). Thompson has introduced an equation for welding time estimation per unit length of a joint (45) which is:

\[ T = T_a + T_b + T_c + T_m + T_r + T_w \]  \hspace{1cm} (45)

where \( T_a \) = Arc Time and the other variables are ancillary times such as electrode changing, deslagging, idles, relaxation and so on. Then the equation is modified to:

\[ T = T_a K_1 + T_m K_2 + T_w \]  \hspace{1cm} (45)

where \( K_1 \) and \( K_2 \) are factors. But arc time per unit length of a joint is estimated by equation:

\[ T_a = \frac{4 \ Vt}{d^2 \pi \ \eta} \]  \hspace{1cm} (45)
where V is weld volume, t fusion time per unit length of electrode, d is electrode diameter and $\eta$ is D.E.

Thompson then has created two other equations and graphs by regression approach in (47). One equation gives the length of electrode fused per unit length of a joint against weld size. The next one estimates the net productive time per unit length of a joint against length of electrode fused.

Following the regression analysis approach in (48) he introduces a graph that represents the relation between welding time and weight of fabrication. He also demonstrates that there is no correlation between the welding time per unit weight of a fabrication and average plate thicknesses. He has even followed the approach for assembly time of fabrication to find some relation with either component weight or thicknesses. But the final results have shown such a "high percentage of errors (ref 48 Table III) that he has concluded with some verbal comments in a general view. He believes that "the results relate to the group of arc-welded fabrications and are not necessarily of general application. However similar relationships to those found in this paper will be of value for tank-like constructions made of stiffened flat plate" (48). He has ended up with his book in 1960 (2) giving some guidelines based on the last graphs. There are three major points to be made about Thompson's approach:

First, the regression approach has been used but not logically, except in two cases. One is total welding time against joint length, which is
quite logical. The other is total welding time against component weight. This relation could also be predicted but not so closely. Thompson shows that there is no significant relationship between average plate thickness and either total welding time or welding time per unit length of joints (48 & 49). This is because average plate thickness has not always a constant ratio with the weld size, and, secondly, Thompson has apparently never tried to see if the number of pieces in a component affect the total welding time. Thirdly, every time he has considered the relationship between the dependent variable with only a single independent variable for which this procedure is not so advisable (40), his equations for the welding time per unit length of joint could be criticised based on a designer's need.

Nevertheless, it must be appreciated that, by comparison with all the other literature available, Thompson is the one and only person who has studied fabrication works from a production view in a detailed manner.

Doherty, of the British Welding Institute, has studied welding economy but from a different angle. He is a mathematician and in his work he is much more concerned about consumable and power costs of welding. He has represented an equation for welding cost per unit length of a joint in 1968 (53). Then after some minor modifications finalised it in 1977 (54) in this form:

\[ C_w = C_1 N \times \eta + \frac{K_1}{a} (C_2 + 687 \times C_3 \times D^2) + N \times (g(t) + h(t))v_w \]  

(54)
where \( C_W \) = welding cost rate
\( N \) = number of welding points
\( n \) = reciprocal of duty cycle
\( K \) = geometric constant relating consumable and weld cross-sectional area
\( a \) = electrode efficiency
\( D \) = electrode diameter
\( C_{1-3} \) = consumable power, and labour costs respectively
\( g(t), h(t) \) = functions describing plant and maintenance
\( V_w \) = Production rate

As it can be seen, the third part of the equation is related to the general overhead and the second part is the cost of consumable and power and one notices that the labour cost has not been considered in detail. The parameter \( N \) which stands for number of welding points has been explained as: the number of machines employed or men employed in the case of manual welding (53, page 8). This parameter can have relation with the general output of a shop which could be considered in relation to the fabrication overhead. Furthermore while Doherty has demonstrated in (53 Page 9) that only very small portions of a total welding cost is represented by the consumable and power costs (about 20%) his major effort has been concentrated on this part of welding cost. Finally, the equation has done little to help the designer or his interest. The only application that can be found for the equation is in general cost estimation of a fabrication by a cost estimator. His consideration has got a more mathematical colouration (53, page 10) rather than an engineering one.

McMahon works on what he called "A General Guide to the Costing of
Weldwork" (18) and he has given some useful guides such as the percentage values that the costs of basic operations contribute to a total fabrication cost. Though not proven it is a fair general guide. The tables on weld metal in unit weight per unit length of joint based on joint design is another guide in his work. It is only for butt joints and could be found in many other references such as in (3). He has produced a general equation for labour costs per unit weight of weld deposited:

\[ CL = \frac{\text{Labour rate/hour}}{\text{D.R.} \times \text{D.C.}} \]  \hspace{1cm} (18)

where \( CL \) = Labour costs per kg,

\( \text{D.R.} \) = deposition rate kg/arc hour

\( \text{D.C.} \) = operation factor

This general equation cannot help a designer very much.

4.3.5.2. Welding Cost Equation in Overseas Literature

Four persons have been found interested in this matter: B. Wadhwa, 1974 (52) and O.W. Bladgett, 1963 (3) and Giachino (59), all from the United States, and Czesany, 1971 (6, paper 5) from Austria. Wadhwa has chosen "Standard Cost" approach (see Section 4.2.3.) for estimating labour cost of welding in 1974 (52). The equation he has produced is based on arc time and operation factor (O.F.):

\[ \text{Standard time} = (\text{Arc time} + \text{handling} + \text{cleaning} + \text{miscellaneous times}) \times \text{allowances} \]  \hspace{1cm} (52)
or it can be shown by symbols in this way:

\[ T_{st} = (T_a + T_h + T_c + T_m) \times A \]  \hspace{1cm} (a) \hspace{1cm} (52)

Now if \( T_h = X \cdot T_a \), \( T_c = Y \cdot T_a \), \( T_m = Z \cdot T_a \)
then the equation (a) will be:

\[ T_{st} = T_a (1 + X + Y + Z) \times A \] \hspace{1cm} (52)

If we take \( X + Y + Z = P \), introducing a fit-up factor "F" and a positions factor PF then we have

\[ T_{st} = T_a (1 + P) \times A \times PF \times F \]

where \( P \) is being estimated by:

\[ P = 1 - \frac{OF}{OF} \]

and where \( OF = \) operation factor.

Arc time is calculated by determining size and length of the weld and using a standard chart of arc time per unit length of weld for a given process (52). In this work Wadhwa has defined the weld length as a value that must be determined by estimators, but has no comments on the way that it can be determined for even a simple component. In a table for fit-up factors he has defined a component with a range of 2 to 20 pieces as the simplest fit-up group. This is not considered a proper consideration of a complexity parameter such as number of pieces. Moreover, handling becomes more complicated and difficult with increase
in the number of the pieces in a component as well as the weights. But Wadhwa has not considered the problem from these two points.

Blodgett, 1963, has given a list of "Useful Welding Cost Formulas" in a table (3). But labour time or cost has not been so seriously considered. He has suggested the determination of the weld length and the joint speed, then calculating the labour time based on these variables and the operation factor. Another way, he suggests, is to calculate weld weight by the aid of a table of section area of weld in detail.

Czesany has represented an equation for labour costs of welding in 1971, (6, paper 5) like this:

\[ K_L = \frac{G}{A} \times L \times \frac{100}{E} \text{ unit cost/meter} \]  

(6, paper 5)

where 
- \( G \) = weight of deposited filler metal (Kg/m) 
- \( L \) = labour rate per hour 
- \( A \) = deposition rate (kg/h) and 
- \( E \) = duty cycle (%) 

One may appreciate that these two last solutions are not much help to a designer since calculation of the weight of deposited filler for the whole of the joints of a component is not so easy and a computer cannot make it better.

Giachino has followed the same approach as the last two above mentioned.
4.3.6. Fabrication Costing by Computer

Based on the literature available no-one has produced a programme to estimate fabrication cost so far, since a general solution has not been available. People are using a computer for cost estimation of manufactured products including metal fabrications but in a very lengthy detail. Computers have not yet found their proper applications in cost estimations especially for metal fabrication. They are being used for simple calculations or listing whilst input preparation is taking a long time. Those simple calculations could be done by a small pocket calculator. For these reasons and those mentioned earlier, designers have not yet found any aid in this field.

Computerising welding costs have been started in the UK since 1978. One or two commercial concerns that have introduced a program for welding cost have not introduced any particular solution that they are willing to discuss. From this it could be interpreted that they are still in the trap of the old lengthy approach of input preparation.

The only program available on welding cost has been presented by Doherty (63) from British Welding Institute. This program is based on his last works on welding cost, which has already been discussed in Section 4.3.5.1. and need not be considered further.

4.4. Designers and Costing

4.4.1. Design and Value Engineering

The importance of costs for designers has been emphasised by many designers and value engineers in literature (34, 57, 58, 60). But not many of them have given an explicit guide to it. One may specify the
target cost of a design, based on the market analysis i.e. need and competitors. And value engineering is the technique to evaluate the design at the detail stage. Roberts (34) has suggested ten steps for determining value, and the very first step is to ask; Is its cost proportionate to its usefulness? Jenkin (58) gives an equation for value:

\[
\text{Value} = \frac{\text{Performance}}{\text{Cost}}
\]

But neither has given any suggestion as to the way of finding a cost. Studer's (57) idea is to establish a special group to investigate the cost problem because "cost control by a designer is a difficult item to control and evaluate". (57)

Starkey (60) has discussed the matter in several articles, and has given guidelines for the costing of a total design. He has made no comments on detail-design costing, although his concept on "Pareto distribution" is a simple and helpful idea. The author has found the concept a useful tool in the costing of a fabrication component.

Starkey believes that "It is not necessary that any estimates which a designer makes in order to help him with his design decision making should be highly accurate in an absolute sense, but they must stand comparison if he is to be able to make sensible cost judgment."

But, as Pugh has pointed out (28), this comparative costing cannot help a designer. He cannot live on comparisons for ever because at the end
the design cost must be predicted before a production starts.

4.4.2. Designers and Fabrication Costs

Component costs are a designer's need (56) but very little is to be found on this topic in the literature. Because, as Studer (37) has pointed out, it is difficult to estimate.

The Association of German Engineers, 1969, (35), Brichta, 1972, (64) and Pugh, 1974, (56) have attempted to satisfy this need in different ways. Mahmoud, 1979, (31) has concentrated on turning component cost in his Ph.D Thesis.

Brichta has followed the general comparative approach which is common in value engineering:

\[ X = \frac{\sum_{i=1}^{n} P_i}{nP_{\text{max}}} \]

where \( P_i \) to \( P_n \) are point values for the respective criteria for a given concept. But this approach will never end up giving a component cost.

The Association of German Engineers has firstly classified industrial products based on their percentage cost of material, labour and overhead in the total manufacturing cost. Then a metrology method has been suggested for costing of parts and simple structures (35).

It has been said that "As the same geometric quantities occur in the stress equation and the equation of manufacturing cost of a part it
is always possible to combine them mathematically in a third equation, the so-called metrological equations" (35, page 69). The approach consists of three stages; first to determine stress equation, second, cost equation and third, metrological equation.

In practice the application of this approach is very rare, since it can be used only for very simple parts with a good costing background in its field (35, the example on pages 71 to 75). Moreover, an individual equation must be built up for every single component and at the same time the inputs for the equations must be determined. The determinations of the equation inputs is still involved with costing problems since the specific operation cost is among the parameters to be determined (35, Page 70).

The German approach looks promising for the future, especially when the load line approach (26) follows the same philosophy. This approach has also been used sometimes in A Comparison of Castings and Fabrications (1).

Pugh has investigated component costs for some of the manufacturing processes especially to satisfy a designer need. The unit weight costs of components have been represented by graphs in relation to the components' weights (56). One of the graphs shows the manufacturing cost/kg against the component weight for "mild steel fabrication - unmachined, BS 4360-1972". Whilst this graph has got some advantages and some disadvantages in use, it is the only available help for designers in a quick forecasting of fabrication cost.
Using one independent variable is good in one way because it is very easy to be handled, but it may not be good enough because the result may not have sufficient accuracy. The actual width of the band in the graph should be wider than what it is, in order to cover a more practical range of complexities in a component. This would be demonstrated in Section 6.10. Moreover lack of knowledge about the main parameters involved with the cost may leave a designer in a situation where he might not be able to decide on where to move inside the band.
5.0. COMPONENT INFORMATION FROM COMPANIES

5.1. Introduction

To be realistic it was decided to study the actual fabrications work with the aid of real components and their planning from a variety of different companies. It was considered better to have as much as possible variety in components as well as companies. But from among 26 companies that were asked for help and contributions, only six companies were found to be interested in this matter. After the first visits to each of these six, which were held with either the cost estimators or production planners, only four of them were able to permit an access to their information. No designer even by chance has been found to show any enthusiasm in this matter. Costing is totally remote from designers' activities, rather it is estimators that take care of it. It took almost 14 months before the final information was received. About eighty different components have been considered together with planning sheets. But after initial studies, only 58 components information were found fairly complete and detailed for further investigation.

The information gained has been used in establishing a solution for labour time estimation. The four companies' components have been considered as four groups which from now on will be referred to by initials, i.e.

<table>
<thead>
<tr>
<th>Company Name</th>
<th>Names called in this work</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Company A</td>
<td>Group A or Group 1</td>
</tr>
<tr>
<td>2. Company B</td>
<td>Group B or Group 2</td>
</tr>
<tr>
<td>3. Company C</td>
<td>Group C or Group 3</td>
</tr>
<tr>
<td>4. Company D</td>
<td>Group D or Group 4</td>
</tr>
</tbody>
</table>
5.2. Shop floor Study

During several visits to each of the six companies mentioned in Section 5.1. a study of fabrication processes in the shops was also carried out. The practical knowledge collected from this experience has been found to be a very useful tool in further analysis of the components' information, as well as in finding the economic design aspects in fabrication.

Machines, equipment and works in the shops are almost similar but with some exceptions. The differences are mainly because the products as well as batch quantities are not the same.

5.2.1. Company A

Products of Company A are in the heavy machinery field, such as crushers and heavy structures, with a batch size of one or two. The shop has some special equipment for edge preparations in curves. Components made of heavy thick plates do not require jigs very often, unless in some special dimensional control of main pieces or to maintain parallelism. A general purpose reciprocal die press is in use to cut square sections up to a certain size. The distortions in these cuts is not important and could satisfy the needs. Plate thicknesses range from 10 to 100mm. They are being cut either by semi automatic or hand torch oxygen cuttings. Thick plates are tested for internal defects (lamination) before being cut. The smoothness of their cut edges is also checked and will be repaired and ground if necessary. This process is called fettling and cleaning. Joints are welded in horizontal position mainly by semi-automatic CO2 welding. The critical joints in heavy and thick
material components would be tested for the first product only. A component will be inspected once after assembly and tack welding, and the next time at the end of the welding process. Component weight may be as high as 15000kg. Details of processes are being decided by fabricators. Wastage is more than what it should be specially in thicker plates. A piece of unused plate will be kept for a few days and if still not used then it is scrap.

5.2.2. Company B

Products from Company B are much lighter than from Company A. The heaviest components are usually less than a 1000kg in weight and the range of metal thicknesses is from sheets up to 25mm. Welding is mainly semi-automatic with a range of wire thickness from 0.9 to 1.2 which is fixed for different machines. The batch quantity may vary between 10 to 20 and very seldom more. Special jigs are designed for almost all of the fairly complex components. This is done when a detailed design is received in the planning department. A process planner decides on the choice of processes and the equipment. The machines are mostly the same as they are in Company A. For one particular component a special jig was used during its assembly and welding in order to keep the precision of the product within a relatively high tolerance limit. Scrap in some areas might be as high as 30%.

5.2.3. Company C

The range of weights and thicknesses of components from Company C are almost the same as from Company B. But the batch quantity never exceeds five whilst the general accuracies are higher than in B. The straightness
of pieces of more than a certain size are checked and corrected by a horizontal hammering machine. Moreover the common joining process is manual welding (MMA).

5.2.4. Company D

In Company D the batch quantity is one off. In some components the number of pieces is quite high (up to 200). This is the characteristic of large components made of fairly thin plate or sections; the component requiring high rigidity and strength. The use of jigs in this shop depends on component complexities and accuracies. They try to minimise scrap by considering several pieces together in cuttings. This policy is more practical when the component pieces are mostly of the same thickness and of simple shapes. This could be assumed to be one of the particular features for the components in this company.

5.3. The Variety of Components and Complexities

This section is concerned with the basic information on the components that have been used as data for the fabrication time consideration in Section 6.10.8. Some of the differences of these 58 components are related to the general features of a shop, which have been discussed in Section 5.2. The others are being introduced here in the table (5.1).
<table>
<thead>
<tr>
<th>Varieties</th>
<th>Group 'A'</th>
<th>Group 'B'</th>
<th>Group 'C'</th>
<th>Group 'D'</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weights kg</td>
<td>940 - 11000</td>
<td>2.5 - 180</td>
<td>10 - 2680</td>
<td>1.5 - 1480</td>
</tr>
<tr>
<td>No. of pieces</td>
<td>37 - 59</td>
<td>3 - 60</td>
<td>2 - 72</td>
<td>2 - 165</td>
</tr>
<tr>
<td>No. of items</td>
<td>17 - 25</td>
<td>2 - 30</td>
<td>2 - 44</td>
<td>2 - 72</td>
</tr>
<tr>
<td>Thickness mm</td>
<td>15 - 75</td>
<td>3 - 25</td>
<td>3 - 50</td>
<td>5 - 20</td>
</tr>
<tr>
<td>Weld size mm</td>
<td>12 - 35</td>
<td>3 - 12</td>
<td>3 - 12</td>
<td>3 - 12</td>
</tr>
<tr>
<td>Special feature</td>
<td>Edge preps.</td>
<td>-</td>
<td>MMA welding</td>
<td>-</td>
</tr>
<tr>
<td>Piece prep. time min.</td>
<td>5400 - 24000</td>
<td>3.5 - 130</td>
<td>38 - 670</td>
<td>16 - 3750</td>
</tr>
<tr>
<td>Welding &amp; Assembly min.</td>
<td>10500 - 51600</td>
<td>5.5 - 690</td>
<td>55 - 5570</td>
<td>40 - 35540</td>
</tr>
<tr>
<td>Total operation time</td>
<td>15900 - 75600</td>
<td>9 - 820</td>
<td>93 - 6240</td>
<td>56 - 39290</td>
</tr>
<tr>
<td>No. of Components</td>
<td>5</td>
<td>19</td>
<td>20</td>
<td>14</td>
</tr>
</tbody>
</table>

Then the varieties for all of the components are:

- Weight 1.5 to 11000 kg
- Number of pieces 2 to 165
- Number of items 2 to 72
- Thickness 3 to 75 mm
- Weld size 3 to 35 mm
- Piece prep. time 3.5 to 24000 min.
- Weld & Assembly time 5.5 to 51600 min.
- Total time 9 to 75600 min.
5.4. The Production Planning

Whilst there is no particular production planning in Company A, every detail of processes except inspection being decided by the fabricators, in Company B the processes are all specified by a production planner based on detailed drawings. In "A" the times are split into three parts; cutting, some of extra process plus assembly, and weldings. No setting time is specified. Fabrication times are being specified based on a study of the general assembly drawings prior to the production of the detailed drawings. The company may revise the Planned times due to a fabricator request from time to time, since the payment in the shop is based on piece work.

In Company B component planning consists of detail processing time for piece preparation, but for assembly and welding they are given either in a total value or sometimes the subassembly times are separated. The planning department in B have some background of work study mainly on cutting processes. But for welding and assembly they usually follow some personal guidelines found from experience.

This type of detail estimation which is quite lengthy could not find any application in design work.

Planning in Companies C and D is similar to B but with less detail, accuracy and certainty. The pay policy in C is similar to B which is weekly, whereas in D the fabricators will get some bonus if they were able to finish a work within less than time allowed.
5.5. More about Estimators

Every estimator used the principles in his work based on his personal experience which is different from others. They appreciate the length of the work as well as inaccuracies particularly in welding times for which they have not been able to find a fairly accurate and reliable approach so far. They also believe that the time estimations of a fabricated component is one of the most difficult and complex jobs they are involved with.

An estimator in Company A has classified the components in several groups and sub groups. This classification is based on the type of work, material type, thickness and the weight. For a particular component he searches first to find a similarity with the other components which are familiar to him. Then considering the other parameters with the aid of rule of thumb, he specifies a percentage of component weight as the weld weight and works out the fabrication time based on the weld weight. This detail of one of the time estimators approach has been given here as an example to illustrate that every estimator's approach consists of some facts, some logic, some lack of knowledge and some misunderstanding of the work. If one knew that in some companies an estimator may take a long time to measure all the lengths of the welds in a complex component using a "map wheel", he would certainly appreciate any trial and error approach that is being used by these people to reduce the lengthy job of time estimation. The facts and logic in the approach above mentioned are: component similarities, thickness which is somehow related to the weld size and the amount of weld which could be related to the welding time, as has been found previously (See Section 4.3.5.).
But a lack of knowledge and misunderstanding make the estimator unable to relate those facts in a proper and meaningful way. First of all he does not know that a designer never follows the same approach while designing a component that in an estimator's opinion looks similar to another component. Secondly, as is discussed in Chapter 6, weight and thicknesses are not the only parameters that affect a fabrication time, and yet their effects should be studied properly. Ignoring one important parameter and giving extra weighting to another parameter may lead to a wrong conclusion. Thicknesses have not always the same ratio with weld size. The relation between, for instance, the weight of two pieces that have been joined together with the same joint length is not linear that one can estimate one, using the other in this way. In other words, the weight ratio of two similar components is not equal to the ratio of the weld weights. If for two similar components such an approach did work, there should be other reasons for it. And finally how many groups are required to cover all component varieties exist.

The above discussion is an analysis of one of the present solutions being used in industry by a time estimator.

In another company the estimator is using a table, created by himself, to estimate flame cutting times. But the basic data in the table does not follow the time values in the references available. Welding times in another company were also considered similarly.
5.6. The Results of Questionnaire

A few months after starting this work a questionnaire was prepared to collect relevant information from different companies and sources (see Appendix B). As it has been mentioned in Section 5.1., unfortunately most of the people that the author tried to bring their enthusiasm to this subject have shown little interest. Even in the six companies that have been visited no designer found in touch. Only six completed copies of the questionnaire were filled, based on personal observations or from the conversations with either time estimators, production planners, production engineers, shop stewards, fabricators or other people in the shops.

Most of the results have been produced in the previous sections of this chapter and the conclusion is presented here.

5.6.1. Work in General

Metal fabrication by welding process and in low to medium batch quantities has found most application with weldable steel and with manual or semi-automatic welding. The machines and processes in use are generally the same. Special jigs will have more uses when a batch quantity increases. Components are being produced in a very wide range by this process. Time estimation of this work is difficult for the estimators. They do not follow a specified and logical approach for this purpose. Computers are in use by time estimators to do the arithmetic and to provide the lists. None of the approaches suggested in literature for this purpose is in use.
Collecting proper information for this purpose is very difficult and anyone may be trapped by the information collected only from one company. Therefore the number of components as well as the number of companies should be adequate to compensate for the inaccuracies.

5.6.2. Designers

Designers in industry are not involved in design costing directly. They never think about actual cost of a design while designing unless triggered by the comments they receive from either a production engineer or a cost estimator. They do not believe in design costing as a part of design activities. Their works are being judged and revised by other people above mentioned, whereas estimators (designers' advisers) need help to get rid of uncertainties. Designers with lack of knowledge of production processes have been pointed out by the people who are involved in this field. They follow the same approach in their work as time estimators do at present time, i.e. trial and error. In brief, they do not consciously control the economy of a design. Let us say that at the moment time estimators require some help to estimate labour time of fabricated components in order to be able to help designers.
6.0. THE APPROACH AND THE SOLUTION

6.1. Labour Time as a base for fabrication cost

The general equation for manufacturing cost of metal fabrication has been introduced in Section 3.2., equation 3.3 which is:

\[ C_{fab} = (W + W_s x C_m + T_{fab} x (FOH) x C_1 + W_{el} x C_{el} \quad (6.1) \]

where \( C_{fab} \) = Manufacturing cost, \( W \) = Component weight, \( W_s \) = Scrap, \( T_{fab} \) = Total manufacturing time, \( FOH \) = Overhead factor, \( W_{el} \) = Electrode weight and \( C_m, C_1 \) and \( C_{el} \) are material, labour and electrode rate respectively.

6.1.1. Material Cost and Overhead

The material cost of a component can easily be estimated. The only requirement is component weight and the material cost rate. Material cost indexes published in "Machinery and Production Engineering", have shown that steel cost rate does not usually change significantly during a fairly long period of time, say one year. On the other hand, material rate changes are always below labour rate changes (36). So, one may take this parameter as a constant while the changes are negligible. The overhead factor \( FOH \) is almost always constant for a shop. It must be noted that "FOH" in a company may not be the same for all manufacturing processes. But it is common to consider it as a constant for all of the components being manufactured by the same process.
6.1.2. Consumables

Electrode consumption depend on the labour time, E.E. and D.C. It is commonly considered as being based on labour cost or included with overhead costs.

6.1.3. Conclusion

Therefore the only part of the cost that is basic and usually cumbersome is the labour cost or labour time. This work therefore is concerned mainly with the labour time together with a general view of the whole economic design of fabricated components.

Nevertheless, in the following consideration, the author has also been concerned with the ease of material costing in relation to the labour costs. In order to do this it was decided to get the most benefit out of the variable which is common to the two i.e. material and labour cost.

6.2. Specification

Like any other design problem, it was decided to apply a design approach to this work i.e. the same stages that a designer must pass through during any design activity should have been passed through in this work. It has always been the intention of the author to ensure that this work retains an explicit design flavour. Wherever necessary, particular design aspects have been pointed out and warnings given.

The stages of the work that have been covered so far are: literature survey, analysis of processes involved and the problems, costing in industry and the study of present solutions (competitors). Now at this
Stage the specification for a solution is to be presented. Since the majority of the specification of this work has been defined in previous chapters there is no need to duplicate them here in detail, but a summary of the main points is considered worthwhile.

6.2.1. Envelope of the work

This is the economic control of a rough fabricated component within the designer work-envelope. So the capability of a designer and the shop facilities could be assumed as the main conditions to apply to a method for controlling costs. The method must be simple, easy to use, quick and with sufficient accuracy. Machining as well as the other manufacturing processes are not covered in this consideration. The method has to be applicable in any company, and not dependent on any particular one.

6.2.2. Size Variety

The variety of component sizes covered by this method is wide and caters for material thicknesses from 5 to 100mm and in plates, sections and hollow section forms in commonly available sizes. Component weight may be from 1 to 11000kg with up to 200 pieces.

6.2.3. Component features

It is a fabrication for use in mechanical engineering. Shipbuilding, tanks, pipelines and the like have not been considered in this work.

6.2.4. Material

Mainly it is weldable steel based on B.S. 4360 1968 and parent pieces of
a component are assumed to be of the same material.

6.2.5. Processes involved

The processes that have been explained in Section 2.6. would be covered by this method.

6.2.6. Feasibility assumptions

Since the studied data have been collected from a practical environment, it is assumed that any impractical manufacturing process is not acceptable. The acceptable cutting processes are based on the Table 4.5 in Ref. 4 (see Table 6.2) and also the guidelines in Refs. 8 and 10. The practical choice of electrode type (coating and size), welding current and voltages, as well as joint position and the accessibility of joints are the basic assumptions on this matter unless otherwise stated.

6.2.7. Environment

It is assumed that the component is to be manufactured in a shop with normal environment. Specially welding is done in the shop and not on site, assisted where necessary by some handling equipment. The joints are to be welded either in the horizontal or flat position. The working temperature is above 0°C, since for temperature less than 0°C preheating for any material thickness is necessary (B.S. 1856). Any uncommon environment such as working under high pressure or under water are not within the specification.

6.2.8. Standards

All of the relevant British Standards which are somehow related to this
work are listed in Appendix A. Standard data for arc welding (19), data from equipment and electrode manufactures are the other applicable basic references.

6.3. The Principles of the Solution

In controlling the economy of a product one may use different tools. It may be a verbal guideline pointing out those component features that either involve the consumption of excessive material or labour. This argument is valid when the work type and the material have already been chosen i.e. the rates for material and labour are assumed to be fixed. In this case an analyst may try to correlate cost criteria, based on the guideline, against the manufacturing features of a component. At the end of such a judgement, one may decide on the optimum choice of a component cost features, but one still does not know the cost of the component.

In order to get the manufacturing cost or time of a component one may need a computing tool to apply the physical values of the manufacturing features such as size, length, area, speed, weight, current, rate and so on. These values are independent variables of a component which must be known. The solution may be used either manually with an equation, a graph, a nomograph or a program running on a computer. To estimate the manufacturing time of a component one needs first to determine the independent variables and then apply the solution to obtain the time required. As one may have noticed the simplicity of the solution depends on two main factors. One is the ease of determination of independent variables and the other is the simplicity of the solution itself. In
other words if the variables are difficult to determine then the solution is not simple enough, and if the solution itself is cumbersome and takes too much time to be applied it is also not a very good one. The remedy for the second case is to use a programmable calculator to reduce the time spent in the calculation. Of course this could be considered a disadvantage of a solution. But when the independent variables are difficult to determine there may be no alternative to it.

To construct an approach to a solution, the main principle is to select those relevant independent variables that can easily be determined. Since a designer's task is to forecast the manufacturing cost of a component, that has not yet been produced, then the variables must also be chosen within that circumstance. Consequently until a proper solution, based on easy and simple variables, is available, even a computer cannot assist the estimation to any great extent.

In general, one may, for ease of determination, change from a direct variable to an indirect variable. For instance, if the cost of a building depends directly on the volume of the building which is difficult to determine, instead one may apply the number of the rooms in the building, which is very easy to count.

6.4. Variables affecting manufacturing time

Many independent variables are involved with a fabrication labour time. Thus the first step is to find all of these variables and understand their effect on the labour time.
6.4.1. The Variables

The manufacturing time consists of operation times and setting times. On the other hand the total manufacturing time for a fabrication is the sum of all processing times i.e. mark-out, cut off, bending, edge preparation, sub-assembly and assembly, tack weld, finish weld and so on. Therefore to cover the whole process one may consider first all the possible variables affecting the processing times. Here is a list of possible variables.

1. Cutting length
2. Thickness
3. Number of pieces
4. Number of items
5. Variety in thicknesses
6. Complexity in pieces
7. Variety in piece weights
8. Volume
9. Weight
10. Material forms & shapes
11. Edge type
12. Edge preparation length
13. Complexities in edges
14. Joint type
15. Joint variety
16. Weld size
17. Weld length
18. Intermittent weld
19. Load type & application
20. Batch quantity
21. Accuracy
22. Type of processing machine
23. Number of processes
24. Number of subassemblies
25. Number of passes
26. Handling & positioner equipment
27. Jigs and fixtures
28. Joint accessibilities
28.2 Weld position
29. Electrode type
30. Electrode size
31. Current & voltage
32. Inspections
33. Workman skill
34. D.R.
35. Electrode efficiencies E.E.
36. Welding speed
37. Learning curve
38. Shop efficiency
39. D.C. or O.F.
40. Type of work
6.4.2. Discussion on the Variables

Some of the items in the list that have already been discussed in Section 2.6. are marked with an asterisk (*). The others will be discussed here.

6.4.2.1. Cutting Length

This is a direct variable in estimating the cutting time of a piece when the cutting time per unit length is known. When the cutting time is very short such as for shears, this variable is not so active.

6.4.2.2. Thickness

Cutting speed, especially in oxygen cutting process, is reduced by the increase of material thickness. But when, for instance, a material thickness is doubled the cutting length for the same weight of material will reduce by 30%. Therefore, these two variables, i.e. thickness and cutting length have some interaction. As will be shown in Section 6.8.2.5, in general the increase of plate thickness for a wide range will slightly increase the cutting time. Moreover the less the plate thickness, the more likelihood there is to cut the material by a short time process such as shearing.

When a fillet weld is designed to be full strength, the weld size is equal to 75% (7) of the parent material thickness (3). This relationship enables plate thickness to be used instead of weld size in the estimation of welding time.

6.4.2.3. Number of pieces \( N \)

This is one of the very effective variables in cutting time as well as
in assembly and welding time. Obviously when one piece takes, say, T minutes to be cut from the raw material, N pieces of the same size will take N x T minutes. The same argument may be used for one joint in comparison with N similar joints. In assembly, also, an increase in the number of pieces will increase the assembly time. Thus the greater the number of a component's pieces, the greater will be the manufacturing time.

6.4.2.4. Number of items "I"

I is defined as the variety of pieces in a component, i.e. the number of different types of pieces. It affects the piece preparation time, i.e. cutting, bending and edge preparation, and also the set up and assembly time. However, the greatest effect of this variable is upon setting time rather than operation times. Since the process is carried out for every single item no matter how many pieces are to be produced of that item. For instance, if a component is made of 50 pieces and the piece variety is, say, 10:

\[ N = 50 \quad \text{and} \quad I = 10 \]

In this example, the cutting process will differ with the variation in items so that the process and the machine should be reset 10 times. There is a similar argument for the assembly times, but the relationship is not so straightforward. Jig complexities also depend on the parameter I.
6.4.2.5. Variety in thicknesses of raw material

This variable which is defined as one of the piece variety features may also affect the setting time of the cutting process in particular. In oxygen cuttings, for instance, if all of the pieces in a component have the same plate thickness, the initial handling of the plate and the machine setting time will be much less than when the pieces to be cut are from different raw material in shapes and sizes. The effects of this upon the component design and the material wastage is discussed later in Section 6.12.

6.4.2.6. Piece complexity

The complexity of the pieces in a component affect manufacturing time in many different ways. It may make cutting operation either difficult or lengthy. For instance a simple square piece from thin plates, say 5mm thick, could be cut by a hydraulic shear in a very short time while for a complex shape of the same material the cutting process may be either oxygen cutting or nibbling which in comparison with shear cutting are lengthy processes. Another example of complexity is with cutting of irregular shapes in sections which may be quite difficult to do. These complexities also have side effects on the assembly and welding times, since they may cause difficulties in set up or fit up or even create awkward joints for welding. The important point to be made here is that, as such, these features are very difficult to quantify in a manufacturing time. It is not only useful but also possible to differentiate between the piece complexities based on the common processes in a shop. The weight of a complexity must be considered carefully since it may have multiple effects on a manufacturing time.
6.4.2.7. **Variety in piece weights**

Piece weights in a component are not usually identical. The heaviest pieces are usually very few by comparison with the number of lighter pieces. In practice the inequality of the piece weights becomes wider with the increase of the component weight and number of the pieces. Piece weights in a component could vary from several thousand kilograms down to a few kg.

6.4.2.8. **Component volume or component envelope**

At the first glance, one may consider component envelope or volume as an important and obvious feature related to manufacturing time. One may argue that the bigger the component the more the manufacturing time for it. But this is not necessarily true since, for example, by adding to or eliminating from a component only one relatively small piece, the volume can be changed dramatically (Piece 1, Fig. 6.1), while many other pieces could be added to a component without changing the volume (see stiffeners in Fig. 6.1).
6.4.2.9. Component Weight \"W\"

In contrast with component envelope, weight is a considerable variable in relation with manufacturing costs. The material cost of a component is a part of its manufacturing cost. At the same time the ratio between material cost and labour cost for any type of product must be kept within a particular range (2). Therefore, there must be some relation between labour cost and material cost, i.e. a relation between a component weight and the manufacturing time. This relation is not so fixed as might be expected since the variety in fabricated component is so wide. In reality the weight of a component is not directly related to the work done upon it, despite what one may find in (41), but it is accepted as one of the important component features. This has been justified by so many experts in this field that some of them have been referred to in Chapter 4. One may appreciate the important advice given in (4):

"GOOD WELD DESIGN is the RIGHT AMOUNT of the RIGHT MATERIAL in the RIGHT PLACE".

Thus one would certainly accept that there should be some relationship between a component weight and its manufacturing time.

6.4.2.10. Edge Type

Square edges are the simplest edge types. Other edges need extra processing i.e. extra time to be produced. A $45^\circ$ bevelled edge is the next simplest in practice and it is the edge most commonly used for plate thicknesses above 20mm, when full strength joints are required. More discussion on edges can be found in Section 2.6.1.5. But it must
be added that edges other than square are not being produced only to satisfy the joint strength and reliability. They are more economical in comparison with the same strength squared edge joint if the process is one of the shop routines i.e. normal.

6.4.2.11. Edge Preparation Length

Edge preparation length like any other cutting length does affect the manufacturing time (see Section 6.4.2.1. Cutting Length). Edge preparation takes more time, both in setting and operation, than a square edge for the same plate. The accuracy is also more important because inaccuracy in edges will increase the welding time (2, page 45).

6.4.2.12. Edge Complexity

Apart from edge type which may be simple or complex (Section 6.4.2.10) a simple edge, for any type of edge, is one in a straight line. Curved edges are more difficult to produce especially when the proper equipment is not available. In some shops, special equipment is used to produce circular edges. Curved edges other than circular are very difficult to produce.

6.4.2.13. Joints variety

A component commonly has joints in different types and sizes. This variety can cause an increase in labour time, since the assessment of the welding could become more lengthy. It may take longer time for inspection and control. Any mistake caused by a complex variety of joints may require repair or over work.
6.4.2.14. Weld size and Weld length

Certainly weld size affects welding time as well as the consumables.

An increase of weld size, say, from \( a \) to \( K_a \), Fig. 6.2, will change the weld volume from \( V_1 = \frac{1}{2} a^2 \) to \( V_2 = \frac{K^2 a^2 K}{2} \).

i.e. \( \frac{V_2}{V_1} = K^2 \). Thus if \( K = 2 \), \( \frac{V_2}{V_1} = 4 \).

The weld size should be kept as small as possible for economy (3). Although weld length is an important variable in welding time, it should be noted that change in weld length has relatively less effect on welding time than change in weld size.

In almost all of the present solutions for welding time estimation, reproduced in Chapter 4, weld length is amongst the variables and it must be measured from a component drawing.

6.4.2.15. Load type and Load application

In designing a fabricated component subjected to a load, the load has basically three characteristics i.e. quantity, type and application.
A load quantity could be in balance with the amount of the material economically only when the material has been chosen with regard to the load type and load application. The load type and application affect the choice of material as well as the thicknesses, joint type, weld sizes, joint locations, weight, number of the pieces and the other details of a component (3 parts 2 & 3). A section in shape which may be suitable, for instance, for a tensile load may not necessarily be a good choice for compression or bending load and vice versa. A proper location of a weld to resist a couple in a member may not be a proper one when the member is subjected to a tensile load, Fig. 6.3. When a component is subjected to a serious dynamic load the design of joints and the pieces are not the same as with a static load, Fig. 6.4. Rigidity, strength, damping, impact strength are load features that may affect the design. The economy of a component is therefore considered with regard to the load qualities as well as load quantities. It is considered that when a component is subjected to a serious load, the design is much more economical in comparison with the design of a component with no important load. Since in the first case the material and weld size required are checked through by stress analysis, whereas in the second case usually the material and welds are oversize and more than required by the load.

6.4.2.16. Number of Processes

Every single operational process in fabrication incurs setting time as well as operations time. The number of processes for a component is not always equal to the number of pieces. Because in some cases a piece could require more than one cutting process. Moreover, bending, edge
Figure 6.3

This weld is approximately 30% stronger than this per unit length. Ref. (4)

Figure 6.4 For Fatigue Loading

Recommended | Try to avoid

Ref. (4)
preparation, straightening are other possible extra processes in a piece preparation. Also the number of subassemblies may vary from one component to another. A designer may find it difficult to work out the number of processes involved in a fabrication. It is his responsibility to recognise the design complexities in order to be able to design with economy even though they are within the production area.

6.4.2.17. Number of Sub-assemblies

It has been suggested that in order to reduce the fabrication time, a complex component must be broken down into a number of subassemblies. This is to reduce the handling problems and the cost. A reasonable number of subassemblies should be chosen to minimise the handling cost and also to make the joints accessible. Although this is a decision usually made by a production engineer, a designer should have enough knowledge about it, since extra subassemblies caused by a bad design will necessitate more work.

6.4.2.18. Number of Passes

The number of passes required to produce a joint depends on the detail of the welding process as well as the electrode size and the weld size itself. A wrong choice of a weld size could increase the number of passes, i.e. increase in welding cost. Therefore in relation to a weld size (Section 6.4.2.14) the welding time for a joint depends on the number of passes required.

6.4.2.19. Electrode type, size and efficiency - Current & Voltage

These five parameters are totally outside a designer's reach. It
depends especially on a welder's decision, his skill and also the equipment available. All five items affect welding time, together with deposition rate (DR) which is also outside a designer's hand.

6.4.2.20. Labour Skill

When an operation depends upon skilled labour, it means that the process is concerned with special manual work. This will increase the labour cost. Any feature in a component which calls for a special skill or care in processing, will increase the labour cost significantly, no matter how much percentage of that particular process is involved with the skill. On the other hand, the general skill in a shop could affect the manufacturing time of a fabrication. Because the duty cycle in a shop is related to the general skill of the workman.

6.4.2.21. Deposition Rate - Welding Speed

These two manufacturing characteristics are also shop features about which a designer may know very little. They are inter-related to each other and are related to electrode types, power characteristics and labour skill (see Section 6.4.2.19,20).

\[ D.R. = \text{Weight of weld deposited in a unit of time} \]
\[ \text{Welding Speed} = \text{Length of weld completed in a unit of time}. \]

6.4.2.22. Shop Efficiency

This variable depends on the shop productivity. The total manufacturing cost is related to it. But it is considered in the manufacturing overhead cost (OH) and is the same for all of the products in a particular shop.
6.4.2.23. **Work Type**

This parameter refers to the difficulties, irregularities and accuracies involved in the manufacturing process of a component in comparison with the general standard levels of routine work in a shop. When the standard level in a shop is relatively high a design within the same standard can be produced in a shorter time than if it was produced in a lower standard shop. By contrast a component with a relatively low standard of work may cost more if it was produced in a shop with high standards. Of course this argument is not so straightforward in practice.

6.4.2.24. **Conclusion**

The variables listed in Section 6.4.1. can be classified in three different groups. The first group consists of the variables directly related to a component detail. Items 1 to 20 are in this category. These features or variables are readily available to a designer since they are present in a component drawing. Item 19 is not in a component drawing but it is known to the designer. The second group consists of the production features of a component. Items 21 to 33 are, or could be, common knowledge to a production engineer. This information is usually available in a shop. Item 21 "accuracies" is specified in the drawings but it is a production feature to achieve it and it depends on the shop facilities. The last group, items 34 to 41, consists of variables which would be within the compass of a planner or a cost estimator. They are mainly general characteristics of a shop from an economical viewpoint.

Some of the variables are very difficult to quantify although their
effects on the manufacturing times are significant. Items 5,6,7,13,15 and 19 in the first group and items 21,26,27,28,32 and 33 in the second and third groups, are with this particular feature. Some of the items do not have so significant a time effect as was thought at the beginning of this consideration, i.e. items 8,15 and 24. Some others could be almost treated as constant parameters in a manufacturing time estimation, e.g. items 20,21,23,26,33,37,38 and 39. They are almost constant for all the fabricated components in a shop, but sometimes there are exceptions.

It could be noticed that some of the variables are interrelated to one another, such as those which have been mentioned in Sections (6.4.2.19, 20 & 21). Then proper choice of variables should therefore be based on these interrelations.

6.4.3. Variable Choice

It was felt that in order to satisfy a designer's need "in economic control of a fabricated component at the design stage", the solution should be based on three major points:

1. Designer knowledge
2. Ease of obtaining variables
3. Minimum possible number of variables.

6.4.3.1. Preferred Variables

The general principle for a solution, and the possible variables affecting manufacturing time have been discussed in sections 6.3. and 6.4. It has been noted that the first group of variables listed in section 6.4.1. represents a component's direct features and a designer
has access to all of them. This means that any attempt at cost control in a design would be meaningless if these variables had not yet been specified. But the variables in the other two groups are not usually readily accessible to a designer unless help by a production sector or cost estimator is given. Consequently, the proper usable variables should preferably be chosen from the first group. The variables which are difficult to quantify should be excluded if possible. The difficulties are because one may not be able to specify the proper values.

The variables which behave as a constant for a shop may not need to be introduced into the basic solution. They would be left for later adjustment in the final solution.

The variables that have no significant effect on the result should also not be involved in an original solution. Finally, and one of the most important points, of all variables, those which take a long time to determine are certainly not a good choice for the solution. This vital point has already been discussed in Chapter 4, where the present day solutions are criticised.

It is worthwhile to mention one more point; a multipurpose variable is preferably much better than a single purpose variable in a solution. For instance, a variable such as cutting length is a single purpose variable since it can be used only in a cutting time estimation. But, for example, the number of pieces is a multi-purpose variable since it could be applied in cutting as well as assembly and welding time estimation.
6.4.3.2. **Summary**

It is preferred to choose a variable that -

a) is in the first group of variables (section 6.4.1.)
b) can easily be quantified
c) does not behave as a constant for all of the fabrication produced in a shop
d) has a significant effect on a manufacturing time
e) is easy to determine
f) is a multipurpose variable
g) can be determined prior to production starting.

6.5. **Operation time - Setting time**

It has already been stated that every single processing time consists of two separate parts: setting time and operation time. Setting time for a fabrication depends on the number of the repetition of the processes (i.e. batch quantity), whereas operation time does not. A setting time is usually constant for a general process or machine, whereas an operation time may vary based on the product features. The setting time for a fabricated component depends on the number of the process varieties involved in the manufacturing, whereas operation time may not necessarily be related to that variety. All of these arguments lead to the conclusion that setting times must be considered separately from operation times. It was considered that the main problem is always concerned with operation time estimation, since the variables are not so straightforward as for a setting time. Therefore it was decided to study the operation times first. But wherever a free study of processing time was in progress settings and operation times may be
6.6. Seeking an Approach

In order to achieve the right result within a time limit, searching for a proper approach was felt to be a vital and initial step at the beginning of this work.

One of the most common approaches suggested for similar works is to use a sampling procedure. As has been already noted, the sampling of a fabrication work is possible only when the whole range of the varieties within the data could be studied practically (section 6.4.1., 5.1.). No shop could be found to carry out work on this scale within a reasonable time scale.

Another approach that has been suggested in the literature is the theoretical analysis of motion and work study. This has also been rejected for the same reason and moreover it is considered by the author that a theory needs to be proved in practice. Letters were sent to more than twenty companies in the area seeking information and discussions. But unfortunately very few showed any interest in this matter. Costing a fabrication component by a designer is something that they have never thought about. Therefore it was found very difficult to get proper information from industry. Synthesis of a fabricated component could be followed to a certain extent (section 6.7.1., 6.7.2. and 6.9.). Because of the uncertainty and varieties of the companies' data, it was not possible to use them for a solution before analysing the fabrication processes and the variables. The present day solution could
help very little (Chapter 4). The decision was taken to tackle the problem from different angles by different tools at the same time. Firstly, a study of a component detail with complexities in relation to the processing times was carried out. At the same time an initial synthesis of a simple component was found to be useful. Afterwards an attempt to find a mathematical relationship between each of the cutting, assembly and welding times, and their main independent variables was carried out separately.

The data provided by companies did not all arrive at once but over a considerable period of time. For the components available at the time, their features were analysed against their production planning. An equation was built up based on the information from the most reliable sources available, on cuttings, handlings and weldings. Then using the component drawings from the companies the detail was assessed.

As the information for more components became available, the relationship between every single variable and the component manufacturing times were studied. The inter relation between the component times was also studied. At the end the inter relation between all these studies under the cover of a logical analysis and trial and error procedure came to the final result.

6.7. Initial Analysis

6.7.1. Simplest Component

It was felt that the main processes which could be found in any fabricated component are cutting and joining.
The simplest fabricated component is considered to be the one with the simplest cuts, minimum assembly work and minimum amount of weld. Consequently a component made of two identical pieces was assumed to be the simplest fabricated component (Figure 6.5a). Rectangular shapes, straight line joint, square edges, identical size and thicknesses of pieces and no odd positioning angles were assumed to be as the other component simplicities. Based on these assumptions being accepted, the main independent variables affecting time have been specified automatically. Because the optimum value for variables is when the component cost is minimised i.e. minimum work, minimum material and the most simple one.

Figure 6.5a

Figure 6.5b
6.7.2. Fabrication analysis and time consuming features

Figure 6.5b shows a basic variety in components using the same amount of material. It is assumed that the thicknesses and weld sizes and weight do not change at this stage of consideration. \( t = \text{constant} \), \( t_w = \text{constant} \), \( W = \text{constant} \). Component A has less time consumed than B or \( C_1 + C_2 \). Because of less cutting length, less assembly and less weld length. The result has been represented in the following table.

<table>
<thead>
<tr>
<th></th>
<th>Weight</th>
<th>Cutting length</th>
<th>Assembly</th>
<th>Weld length</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>( W_A )</td>
<td>81</td>
<td>One position</td>
<td>1</td>
</tr>
<tr>
<td>B</td>
<td>( W_B = W_A )</td>
<td>9.661</td>
<td>2</td>
<td>1.4142</td>
</tr>
<tr>
<td>( C_1 + C_2 )</td>
<td>( W_{C1} + W_{C2} = W_A )</td>
<td>11.321</td>
<td>2</td>
<td>1.4142</td>
</tr>
<tr>
<td>( C_1 )</td>
<td>( W_{C1} = \frac{1}{2} W_A )</td>
<td>5.661</td>
<td>1</td>
<td>0.707</td>
</tr>
</tbody>
</table>

Consequently since in the case B or \( C_1 + C_2 \) the material has been split into more pieces than in case A, the cutting as well as assembly and welding work are increased significantly. Thus the number of pieces can be accepted as one of the major factors in a component.

Comparison between A and \( C_1 \) reveals two major points. Firstly, the material ratio between two components similar in shape is not the same as the manufacturing cost ratio (see the table), otherwise one could expect to produce for instance a hundred identical components with the same cost as to produce one similar component from the same material but to a larger scale. Secondly, for two similar components the heavier component requires more work than the other. These results would introduce another major parameter which is component weight. On the other hand, if one starts with one piece, then joins another piece to
Figure 6.6
it and then another and so on the work time will be increased in the same manner. In general, adding one piece to a component will increase the component weight, handling time, number of cuts and number of joints or joint lengths. But with the same amount of material, same pieces and same joint size, if the position and/or the location of the pieces were changed relative to each other, the processing time will not change significantly (see Fig. 6.6. a-g). In some cases like Fig. 6.6.f. or when the pieces locations are very awkward, the assembly and welding time increases considerably. But this may happen very seldomly and it is to be avoided by a designer. It is considered as a component with special complexity. For a case like Fig. 6.6.g. only the weld length has been increased relatively to the others. Thus this is a less important feature which should be considered with other similar features after the main features have been considered (see Section 6.10.11).

6.7.3. Component features versus processing times

To show how a change in a component feature (independent variables) affects the detail time of the main processes involved, a table was prepared (Table 6.1.). The component direct features were chosen because they are - as was already pointed out - the parameters most accessible to a designer. In this table the time effect of every single variable of the detail of the main processes has been considered while the other variables were assumed to be constant.

It was felt that the only weighting that could be applied for the time effects in the table (6.1.) are plus for an increase, no sign for an insignificant change and minus for a decrease in the time, since such
changes in the variables are not directly comparable to each other. Therefore whereever, for instance, a sign (+) has been used it means that an increase in the variable would increase the labour time for that particular part of the process which is under consideration.

The table has been completed based on a general knowledge of processes. It was found that any further detail of processes at this stage will make the table cumbersome, impractical and not at all useful. It has been assumed that the study of variables is carried out in a shop with fixed facilities capable of proper processing.

6.7.3.1. Uncertainties
Symbol (∼) has been used to express uncertainties in the time changes caused by change of a variable. It may be due to either the availability of special equipment, change of the processing machine, opportunities for time saving (or losing) or any other reasons. For instance, if it is (∼+) it means that there might be a significant increase in the time or may not. Similarly, (−∼) means that under certain circumstances a significant decrease might be expected.

It must be noticed that some of the changes in edge preparation times or in bend times depend on the possible existence of these particular processes in the fabrication.

6.7.4. Analysis of Table 6.1.
At first glance one may find that there are variables that a change on any of them may cause a significant change in almost all of the
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The effect of component features on the processing time.

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processing times. These variables influence either operation times or setting times. It is very rare that a variable influences both operation and setting time simultaneously. Variables such as number of pieces (N) and weight (W) have the most effect on operation time, whereas number of items (I) and the batch quantity have the most effect on setting time.

There are variables that have significant effects on one or another main process. Material thickness will affect the operation times for cutting, and edge preparation other than square may change both operation and setting time. Increases in either weld size or weld lengths will increase the welding operation times. But, as it has already been mentioned, the weld size changes relatively have much more effect on welding operation time than the weld length changes.

The increase in some of the variables such as items 1, 11, 12, 19 and 20 create a requirement for extra processes. Whereas increase in the variables such as items 5, 7, 13, 14, 15 and 16 could produce an increase of operation times.

A component having accuracies more than general shop accuracies requires extra times in almost all of the processing stages and this should be considered separately.

Items 10 and 11 have been considered based on item 9 i.e. their time changes have been related to each other. Item 9 represents a change from plates to sections. Then the time effects of items 10 and 11 have
not been evaluated in relation to the others in here. It is assumed that a component is said to be made of sections if 85% of material utilised is cut out of sections and a component is said to be made of plates if 85% of material utilised is cut out of plates (35).

It has been noticed that in most of the cases a designer chooses a weld size for a joint based on the thickness of the parent pieces. It depends also on whether the joint is designed for strength, for some degree of rigidity or the joint is not carrying an important load. Therefore, in many cases, it is possible to inter-relate thickness and the weld size by a proper factor (3, Chap. 6) and apply only one of them as an independent variable in the equations.

Some of the variables do not usually exist in a component such as items 8 and 10. Inside cuts in plates (item 8) and irregular cuts in sections (item 10) can affect processing time when they exist with relatively large size or considerable amount in a component; this might happen very seldomly. Also item 4 which as an individual variable has no effect on assembly and welding time. It is an item variety feature which may have a side effect on setting time of piece preparation if the change becomes significant.

The effect of the variety in piece weights in a component could provide significant reduction in cutting as well as welding times and this will be discussed in section 6.9.3.1.

6.7.5. Conclusion

At this stage of the work the variables could be classified in the order
of importance as follows:-

\[ a = \text{operation times} \]

\[ a - 1 - \text{Number of pieces } 'N' \]

\[ a - 2 - \text{Pieces weights } 'W_p' \text{ or component weight } 'W' \]

\[ a - 3 - \text{Weld size or leg length } 'tw' \]

\[ a - 4 - \text{Joint length } 'l_j' \]

\[ a - 5 - \text{Plate thickness } 't' \]

\[ a - 6 - \text{Number of edges prepared} \]

\[ a - 7 - \text{Edge lengths (could be equal to } l_j \text{ or not)} \]

\[ a - 8 - \text{Number of bends} \]

\[ a - 9 - \text{Simplicity; sections, pieces weights variations} \]

\[ a - 10 - \text{Complexity; inside cuts, section irregular cuts,} \]

\[ \text{accuracies, load, and any other extra processes.} \]

\[ b = \text{setting times} \]

\[ b - 1 - \text{Batch quantity } 'n' \]

\[ b - 2 - \text{Number of items } 'I' \]

\[ b - 3 - \text{Edge preparation items} \]

\[ b - 4 - \text{Bends items} \]

\[ b - 5 - \text{Irregular cuts} \]

6.8. Cutting Process Analysis

The most applicable cutting process is oxygen cutting, either semi-automatic or manual. The use of these two processes as well as the others have been explained in section 2.6., see also Table 6.2. which is a modified form of Table 4.5. in Ref. 4.
Table 6.2 - Fabrication Design Guide, Material cutting Processes. (4)

<table>
<thead>
<tr>
<th>STANDARD STEEL SHAPE</th>
<th>THICKNESS OR SIZE</th>
<th>ORIGINAL CUT SHAPE</th>
<th>PROCESS SELECTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>H, T, Z, I, Rail</td>
<td>All Size</td>
<td>All Cuts</td>
<td>C</td>
</tr>
<tr>
<td>Channels and Angles</td>
<td>Up to 6 mm</td>
<td>Square or Angular</td>
<td>B</td>
</tr>
<tr>
<td></td>
<td>6 mm to Max.</td>
<td>Square or Angular</td>
<td>B</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>C</td>
</tr>
<tr>
<td>Tubing</td>
<td>Light Wall</td>
<td>Square or Angular</td>
<td>C</td>
</tr>
<tr>
<td></td>
<td>Heavy Wall</td>
<td>Square or Ang.</td>
<td>A</td>
</tr>
<tr>
<td>Pipe</td>
<td>Up to 200 mm</td>
<td>Square or Ang.</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>200 mm to Max.</td>
<td>Square or Ang.</td>
<td>B</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>C</td>
</tr>
<tr>
<td></td>
<td>All</td>
<td>Complex</td>
<td>A</td>
</tr>
<tr>
<td>Round, Hex, Octagon</td>
<td>Up to 20 mm</td>
<td>Square or Ang.</td>
<td>B</td>
</tr>
<tr>
<td></td>
<td>20 to 130 mm</td>
<td>Square or Ang.</td>
<td>B</td>
</tr>
<tr>
<td></td>
<td>130mm to Max.</td>
<td>Square or Ang.</td>
<td>C</td>
</tr>
<tr>
<td>Rectangular Bar</td>
<td>10 to 30 mm</td>
<td>Square or Ang.</td>
<td>C</td>
</tr>
<tr>
<td></td>
<td>30 to 100 mm</td>
<td>Square or Ang.</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>100mm to Max.</td>
<td>Square or Ang.</td>
<td>A</td>
</tr>
<tr>
<td>Plates and Sheets</td>
<td>3 to 10 mm</td>
<td>Straight Sides</td>
<td>C</td>
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<td></td>
<td></td>
<td>Circular</td>
<td>B</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Complex</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>10 to 32 mm</td>
<td>Straight Sides</td>
<td>C</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Circular</td>
<td>B</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Complex</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>32 mm to Max.</td>
<td>Straight Sides</td>
<td>C</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Circular</td>
<td>B</td>
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<tr>
<td></td>
<td></td>
<td>Complex</td>
<td>A</td>
</tr>
</tbody>
</table>

ASSUMPTIONS:
1. Equipment of reasonable capacity is available.
2. All Processes are operator attended

KEYS:
A = Best Method
B = Good Method
C = Satisfactory Method

Diagram of equipment used for cutting processes.
Information on cutting times is fairly rare (4, Chap. 4) & (11, Section 6.1.). The cutting speeds in relation to material thickness for oxygen cutting, either by hand or machine, are tabulated in (11). The table has been adapted here in Table 6.3, representing times per unit length of cuts for different plate thicknesses.

6.8.1. Oxygen Cutting Time

6.8.1.1. Oxygen Cutting by Machine

Figure 6.7. shows variation in the cutting time per unit length of cut against material thicknesses. The graph shows that the relationship between time and the thickness is almost linear. Taking the average of the time values, by the aid of a curve fitting, one arrives at an equation for the relationship as follows (Fig. 6.8.):

\[
T_c = 0.036t + 1.63
\]

(6.2.)

where \( T_c \) = cutting time per unit length of cuts in minutes.

\( t \) = metal thickness in mm

Graphs in Figs. 6.7 and 8 show the relation for a range of thicknesses from 6.35 mm (\( \frac{\frac{1}{4}}{4} \)) to 152.4 (6"). The values for time are the actual cutting time. No handling, allowances or setting time have been included. The waving pattern of the graph could be due to the fact that a cutting tip can only be used economically for two or three consecutive plate thicknesses. Changing a cutting tip to a larger diameter will reduce the gradient of cutting time.
Table 6.3 - CUTTING SPEED AND TIME FOR FLAME CUTTING (Ref. 11)

<table>
<thead>
<tr>
<th>Metal Thickness Inch</th>
<th>Tip Size</th>
<th>Range of Cutting Speed m/min</th>
<th>Range of Cutting Time min/m</th>
<th>Average Time min/m</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Range of</td>
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<td></td>
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<td>Range of</td>
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<tr>
<td>1/4 6.35</td>
<td>0</td>
<td>.51 - .61</td>
<td>1.97 - 1.64</td>
<td>1.8</td>
</tr>
<tr>
<td>3/8 9.53</td>
<td>1</td>
<td>.48 - .58</td>
<td>2.07 - 1.71</td>
<td>1.9</td>
</tr>
<tr>
<td>1/2 12.7</td>
<td>1</td>
<td>.43 - .53</td>
<td>2.32 - 1.87</td>
<td>2.0</td>
</tr>
<tr>
<td>3/4 19.1</td>
<td>2</td>
<td>.38 - .46</td>
<td>2.62 - 2.2</td>
<td>2.41</td>
</tr>
<tr>
<td>1 25.4</td>
<td>2</td>
<td>.36 - .43</td>
<td>2.81 - 2.32</td>
<td>2.56</td>
</tr>
<tr>
<td>1 1/2 38.1</td>
<td>3</td>
<td>.30 - .37</td>
<td>3.28 - 2.72</td>
<td>3.0</td>
</tr>
<tr>
<td>2 50.8</td>
<td>3</td>
<td>.254 - .3</td>
<td>3.94 - 3.28</td>
<td>3.61</td>
</tr>
<tr>
<td>2 1/2 63.5</td>
<td>4</td>
<td>.23 - .28</td>
<td>4.37 - 3.58</td>
<td>4.0</td>
</tr>
<tr>
<td>3 76.2</td>
<td>5</td>
<td>.2 - .245</td>
<td>4.92 - 3.94</td>
<td>4.43</td>
</tr>
<tr>
<td>4 101.6</td>
<td>5</td>
<td>.18 - .22</td>
<td>5.62 - 4.63</td>
<td>5.12</td>
</tr>
<tr>
<td>5 127</td>
<td>6</td>
<td>.15 - .18</td>
<td>6.56 - 5.62</td>
<td>6.09</td>
</tr>
<tr>
<td>6 152.4</td>
<td>6</td>
<td>.13 - .15</td>
<td>7.87 - 6.56</td>
<td>7.21</td>
</tr>
<tr>
<td>8 203.2</td>
<td>7</td>
<td>.10 - .13</td>
<td>9.84 - 7.87</td>
<td>8.86</td>
</tr>
<tr>
<td>10 254</td>
<td>7</td>
<td>.09 - .10</td>
<td>11.25 - 9.84</td>
<td>10.95</td>
</tr>
<tr>
<td>12 304.8</td>
<td>8</td>
<td>.076 - .09</td>
<td>13.12 - 11.25</td>
<td>12.18</td>
</tr>
</tbody>
</table>

| Hand Torch Cutting  |          | Range of                     |                             |                     |
|                     |          | Range of                     |                             |                     |
|                     |          | Range of                     |                             |                     |
| 1/4 6.35            | 0        | .41 - .46                     | 2.46 - 2.2                  | 2.33                |
| 3/8 9.53            | 1        | .37 - .42                     | 2.72 - 2.4                  | 2.56                |
| 1/2 12.7            | 1        | .30 - .37                     | 3.28 - 2.72                 | 3.0                 |
| 3/4 19.1            | 2        | .254 - .33                    | 3.94 - 3.03                 | 3.48                |
| 1 25.4              | 2        | .22 - .30                     | 4.63 - 3.42                 | 4.02                |
| 1 1/2 38.1          | 3        | .15 - .19                     | 6.56 - 5.25                 | 5.9                 |
| 2 50.8              | 3        | .14 - .18                     | 7.16 - 5.62                 | 6.39                |
| 2 1/2 63.5          | 4        | .14 - .17                     | 7.16 - 6.06                 | 6.61                |
| 3 76.2              | 5        | .13 - .17                     | 7.87 - 6.06                 | 6.96                |
| 4 101.6             | 5        | .10 - .13                     | 9.84 - 7.87                 | 8.86                |
| 5 127               | 6        | .09 - .11                     | 11.25 - 8.75                | 10.1                |
| 6 152.4             | 6        | .076 - .10                    | 13.12 - 9.84                | 11.48               |
| 8 203.2             | 7        | .064 - .09                    | 15.75 - .11.25              | 13.5                |
| 10 254              | 7        | .051 - .076                   | 19.70 - 13.12               | 16.41               |
| 12 304.8            | 8        | .038 - .051                   | 26.25 - 19.7                | 23.0                |
Figure 6.8

Cutting Time in min/m

Material Thickness in mm
Figure 6.9 - Flame Cutting by hand torch.

Pure Cutting time (min/m) - Material thickness (mm)
6.8.1.2. Oxygen cutting by hand torch

This process is used for awkward cuts especially in sections and also scrap cuttings. Its use depends on the lack of special facilities in a shop. The process quality and the time is a labour skill function and difficult to control.

The same procedure adopted for machine cutting time is repeated here to achieve an equation for hand cutting times. Fig. 6.9. shows the variation in hand cutting times (minutes per metre) for a range of metal thicknesses.

The scatter in this graph is much more than in Fig. 6.7. because of the human factor and the difficulties in controlling the times. In general the times are greater than the time for machine cutting and the gradient of the variation is higher. As is to be expected, curve fitting has not given a good result with this data (Fig. 6.10). It was noticed that points 6 and 7 are odd and have been eliminated (Fig. 6.11). Final result of the relationship between cutting time and metal thickness is:

$$T_{CH} = 0.062t + 2.23$$  \hspace{1cm} (6.3.)

6.8.1.3. Conclusion

The study of equations 6.2. and 6.3. shows that oxygen cutting times, either by machine or hand, can be accepted to be in linear relationship with metal thickness within the range. For a particular length of cut the time should have a linear relationship with length too. The time for hand cuts
Figure 6.10
Figure 6.11
Figure 6.12
is much greater than for machine. An inter-relation between these two times, for the same plate thicknesses, is shown in Fig. 6.12 and the equation is:

\[ T_{CH} = 1.73 T_{CM} - 0.54 \]  

These three equations (6.2.-4) could not be directly used in time estimations because, firstly, they do not give the whole processing time. Secondly, for a group of cuts, the cutting length is a difficult independent variable yet to be determined.

6.8.2. Piece Cutting Time

The operation and setting time for different cutting processes are given in several charts in (4). The times for oxygen cutting and shearing are in relation to cutting length for various thicknesses where the length is to be determined. The times for power saws are in relation to depth of cuts. Setting times for oxygen cuts by hand and shears are less than 10 minutes whereas in oxygen cutting by machine and sawing, it is about 15 minutes. The shear operation times are usually a portion of a minute. This is for only one stroke operation and not one piece.

The most useful charts are those for oxygen cutting times.

6.8.2.1. Machine Oxygen Cutting Time

The chart for cutting time against length of cut for different thicknesses for machine oxygen cuttings in (4) is reproduced here in Fig. 6.13. Apart from the difficulties involved with the determination of cutting
Figure 6.13

MACHINE FLAME CUT

SETTING TIME 13 min.

Operation Time (Minutes)

Length of Cut per Piece (Inches)

Thickness

- 140
- 120
- 100
- 80
- 60
- 50
- 40
- 30
- 20
- 15
- 10
- 5

0.25''
1.0''
1.5''
2.0''
4.0''
5.0''
6.0''
lengths, the curves have not been prepared with ease of use in mind. One may use a simple graph paper and re-plot the values collected from the chart. The result is shown in Fig. 6.14 which is much more applicable in practice. The author has not been able to find the reason for the graphs being produced in that form. They are not hypothetical graphs since they are with considerable detail. Moreover no mathematical equation has been produced to justify the way of presentation.

Although the charts in (4) are not for general use, it could be accepted that they introduce the basic relation between the times and the independent variables. Fig. 6.14 shows that, even with inaccurate readings of the values, for a constant thickness a linear relation between times and length is acceptable with good accuracy. The lines converge to a point $T \approx 1.5$

Note - Fig. 6.14 has been produced in imperial units i.e. the cutting length as well as the thickness are in inches. The result of the discussion has been converted to metric units in section 6.8.2.3.

Studying the relationships for a constant thickness, say 4 inches, a linear equation may be fitted to the graph which is approximately:

$$T = 0.15 \cdot l + 1.5$$

(a)

where $T$ is operation time in minutes and $l$ is cutting length in inches.
Machine Flame Cutting
Setting Time, 13 min.

Figure 6.14

Operation time (minutes)

Length of Cut per Piece (Inches)
Then for any thickness within the range, in general the equation (a) will be:

$$T = m_1 + 1.5$$  \hspace{1cm} (b)

where $m = f(t)$ which for $t = 4''$ we have $m = 0.15$

The consideration of weights, creating the differences in the charts in Ref. 4 (see appendix C) might be acceptable as the differentiation between one man handling and either two men or equipment handling. It is assumed that the weight ranges, within the 23kg limit, are proportional to the cutting lengths, so that their handling effects and the fatigue allowances are also included in the time.

Another graph has been prepared based on the same information. This time the cutting lengths are fixed and the times are plotted against thicknesses in Fig. 6.15. The curves could be assumed converged to a point, approximately, of $t \approx -1.8$ and $T \approx 1.7$. For the lengths within the range the approximate linear equation which covers the whole range of the thicknesses related to time is:

$$T = n(t + 1.8) + 1.7$$  \hspace{1cm} (c)

where $n = f'(l)$ and, for instance, for $l = 200$ inches $n = 4.9$.

Equations b and c could be combined to find the parameters $m$ and $n$. These equations are:
Figure 6.15 - Machine Flame cut
Cutting time - Plate Thickness, when cutting length is constant.
\[ T_1 = m \ 1 + 1.5 \quad (d) \]
\[ T_2 = n \ (t + 1.8) + 1.7 \]

When \( t = 4'' \), \( m \) in the first equation is \( m = .15 \). Now using these two values in both simultaneous equations, by taking \( T_1 = T_2 \) it will be:

\[ T_1 = T = 0.15 \ 1 + 1.5 \quad 0.15 \ 1 + 1.5 = 5.8n + 1.7 \]
\[ T_2 = T = n \ (4 + 1.8) + 1.7 \]

i.e. \[ 5.8n = 0.15 \ 1 + 1.5 - 1.7 \]

or \[ n = \frac{0.15 \ 1 - .2}{5.8} = \frac{1}{39} (1 - 1.33) \]

Substituting the value of \( n \) in the second equation \( (d) \) will give:

\[ T_2 = \frac{1}{39} (1 - 1.33) \ (t + 1.8) + 1.7 \]

or

\[ T_2 = \frac{1}{39} (t + 1.8) \ 1 + 1.64 - 0.034 \ t \]

The last term in the equation, i.e. \((0.034 \ t)\) is negligible. Because the maximum acceptable value for \( t \) is \( t = 5'' \). Then the last term could be at most:

\[ \text{Max} \ (0.034 \ t) = (0.034 \times 5) = 0.17 \ \text{min} \]
\[ \text{Min} \ (0.034 \ t) = (0.034 \times .25) = 0.0085 \ \text{min} \]
Then the final form of the equation is:

$$ T_2 = \frac{1}{39} [(t + 1.8) + 64] $$  \hspace{1cm} (e)

To evaluate the value of $m$ in equation (b), once more the simultaneous equations (d) will be solved. It was said that when $l = 200$ inches $n = 4$. Substituting these values and taking $T_1 = T_2 = T$:

$$ T_1 = T = mx \cdot 200 + 1.5 $$
$$ T_2 = T = 4.9 \times (t + 1.8) + 1.7 $$

Solving the equation for $m$:

$$ 200 \cdot m = 4.9 \cdot t + 10.52 - 1.5 $$

or

$$ m = \frac{4.9 \cdot t + 9.02}{200} \approx \frac{1}{40.8} \cdot (t + 1.84) $$

Substituting the value of $m$ in equation (b)

$$ T_1 = \frac{1}{40.8} \cdot (t + 1.84) \cdot l + 1.5 $$

$$ T_1 = \frac{1}{40.8} \left[ (t + 1.84)l + 61.2 \right] $$  \hspace{1cm} (f)

There is a slight difference between the results from equation (e) and equation (f) which is because of using approximate approach. The inaccuracies are at most less than 5% where the results from equation (e) are closer than equation (f) to the actual values.
6.8.2.2. Oxygen Cutting by Hand

Using the charts for hand cutting from (4) and following the same approach as the one in section 6.8.2.1. will come to two simultaneous equations (see appendix C):

\[ T_1 = m_1 (1 + 15) + 2.5 \]
\[ T_2 = m_2 (t + 1.4) + 3 \]

Where \( m_1 = f_1 (t) \) and \( m_2 = f_2 (l) \). Solving the equations for \( m_1 \) and \( m_2 \) will come to this result:

\[ m_1 = \frac{9.25 + 6.25t}{115} \]
\[ m_2 = \frac{.191 + 2.35}{3.4} \]

Substituting the values \( m_1 \) and \( m_2 \) in equations (g):

\[ T_1 = \frac{1}{18.4} (t + 1.48) (1 + 15) + 2.5 \approx \frac{1}{18.4} (t + 1.5)(1 + 15) + 2.5 \]
\[ T_2 = \frac{1}{17.895} (1 + 12.37)(t + 1.4) + 3 \approx \frac{1}{18} (t + 1.4)(1 + 12.4) + 3 \]

The differences are considered insignificant.

6.8.2.3. Metrication

Equations (e and h) give cutting times per minutes where thickness \( t \) and cutting length \( l \) are in inches. It has been decided to introduce thicknesses in millimetres and cutting length in metres. Substituting the values:

\[ t \text{ (in mm)} = \frac{t \text{(in inches)}}{25.4} \]
\[ l \text{ (in metres)} = 39.37 \ l \text{ (in inches)} \]
in the equations the results are:

For oxygen cutting by machine:

\[ T_c = 0.04 (t + 46)1 + 1.64 \]  \hspace{1cm} (6.5.)

and for oxygen cutting by hand using the first equation of equation (g):

\[ T_c = 0.0843 (t + 38) (1 + .38) + 2.5 \]  \hspace{1cm} (6.6.)

6.8.2.4. Change of variable from cutting length to piece weight

Since cutting length is a special variable which may not be particularly useful in the other processing stages, it was decided to introduce piece weight instead of cutting length. It is assumed that a piece with a rectangular shape has four sides with a total cutting length of 1. Therefore the effective length of each side is \( \frac{1}{4} \). If the thickness is \( t \) then the piece weight is:

\[ W = \left( \frac{1}{4} \right)^2 \times t \times 7.8 \quad \text{or} \quad l = 4 \times \frac{W}{\sqrt{7.8t}} \]

where \( W \) = piece weight in kg, and the constant 7.8 represents the density of steel. Substituting the value 1 in equations 6.5. and 6.6., we have:

(for machine cutting) \[ T_c = .01 (33 \times t \times t)^{-5} + (\frac{W}{t})^{-5} + 1.64 \]  \hspace{1cm} (6.7.)

(for hand cutting) \[ T_c = 0.121(t + 38)(\frac{W}{t})^{-5} + .032t + 3.7 \]  \hspace{1cm} (6.8.)

Equations 6.5. and 6.6. or 6.7. and 6.8. are the simplest equations for estimating times for oxygen cutting either by machine or by hand,
based on two of the main variables. These results of course depend on the reliability and accuracy of the available data. The proportionality of times with \( W^5 \) and \( t^5 \) are the conclusions from the above discussion that one may come to.

6.8.2.5. The Actual Relation between Cutting Time, \( T \), Piece Weight, \( W \), Thickness, \( t \) and Cutting Length, \( l \).

For a piece with a specified weight, when the thickness increases the cutting length decreases. But the cutting area will increase and so does the cutting time. This can be explained by assuming a square piece with a weight \( W \), thickness \( t \) and a side length of \( l \). Since for a particular material the weight is proportional to the piece volume \( V \), the discussion will be continued with \( V \) instead of \( W \). Then the piece volume is:

\[
V = l^2 \times t
\]

The cutting length for this piece \( L = 4l \) and the cutting area is \( A = 4lt \). If the thickness increases from \( t \) to \( t_1 \) by a factor of \( K \gg 1 \) so that \( t_1 = K \times t \) then:

\[
V = l_1^2 \times t_1 \quad \text{or} \quad l_1^2 = \frac{K}{t} t
\]

Where \( l_1 \) is the side length of the new piece. Therefore:

\[
l^2t = l_1^2 \times Kt \quad \text{or} \quad l_1 = K^{-\frac{5}{2}} \times l
\]
Since $K > 1$ then $K^{-0.5} < 1$ so it is seen how side length and consequently cutting length decreases to $L_1 = 4K^{-0.5}$. But the cutting area for the new piece is $A_1 = 4l_1t_1$ or

$$A_1 = 4l_1t_1 \quad \text{or} \quad A_1 = 4K^{0.5}lt$$

which has been increased by a factor of $K^{0.5}$. So one may expect that for the same weight the thicker the material the greater will be the cutting time.

On the other hand using equation 6.7, two graphs have been plotted. The first one in figure 6.16 shows the cutting times against cutting lengths for constant weights ranges from 5 kg to 500 kg whilst the thicknesses are increased in 10 steps from 5 to 100 mm. The curves show that the cutting times do not increase always with an increase in the cutting length, or the relationship is not what it was expected.

In the second graph (Fig. 6.17), the cutting times are plotted against thicknesses and the result is different from the conclusion of the above discussion.

The changes in the thickness for $t > 20$ does not change the cutting time significantly while for $t < 20$ the increase of thickness will reduce the cutting time. These changes become more significant for heavier pieces. It is because of the interaction of the first and second terms in equation 6.7. which for $t < 46$, the cutting time ($T_c$) decreases when $t$ increases, since the first term, $1/100 (33Wt)^{0.5}$, is
Figure 6.16

CUTTING TIME in minutes

CUTTING LENGTH in meter
much smaller than the second term, \((\frac{7W}{t})^{0.5}\). At \(t \approx 46\) both terms are equal. After that for \(t > 46\) an increase in \(t\) causes an increase in first term which is slightly bigger than the reduction in the second term. As the piece weight becomes heavier the changes become more significant.

If a similar graph to the one in Fig. 6.17 is produced using pure cutting time equation from equation 6.2. the result will be almost the same. Therefore there is no doubt about the time variation shown in figure 6.17. In practice, as the piece weight increases, the left part of the curves (i.e. \(t < 20\)) becomes less in use, since one may find very rare components made of large and relatively thin plates. However, for general conditions, it can be accepted that the main variable in cutting time is weight \((W^5)\) and for \(20 < t < 100\)mm the effect of thickness on cutting time is not very significant i.e. \(\pm 8\%\) (see the variation in the curves). But for thickness \(t < 15\)mm, in particular, \(t\) will become a significant variable affecting operation time. For example, when \(W = 500\)kg, \(t = 10\)mm, therefore side length \(l = 2.53\) metres, the cutting time will increase up to \(20\%\) in comparison with if \(t = 25\)mm.

6.8.3 Assembly and Handling

This part of the work process of fabrication is the least studied part in the literature. It is probably because the detail of the process of this stage is unpredictable. It is relatively easy to put the detail, for instance, of a welding or a cutting process in a proper order and study the whole processing time (Ref. 19, for instance, gives the detail of welding time). But for assembly time this kind of study is not feasible.
since there is no explicit order in the detail of this process and every component is treated in a particular way different with the others. The only common detail for all components is handling and positioning of the pieces.

6.8.3.1. Motion Study and Time

Theoretical study of work and motion could not be applied for this purpose since the work is so complex. Also a lot of detail of the processings may not be known at the design stage. Nevertheless a brief review of the basic facts was found to be useful for better understanding of the main variables.

The time required to perform a given motion depends on four major factors: 1) Body member (arms, legs, etc.), 2) Distance, 3) Weight, 4) Control and accuracy.

The study of the first factor in a fabrication assembly requires the detail of the work. But in general the bigger the component the more the body members become involved in work. In the assembly and handling of the pieces of a small component, arms movements are the only requirement. But for a large component, almost all of the body members will be involved in the process.

Distance and weight of a work piece are more quantifiable variables than the two others in the time estimation of fabrication assembly. The fourth factor, control and accuracy, could be considered as a part of the whole accuracy required in a fabrication.
6.8.3.2. Weight and Distance

Two approaches have been suggested for work-factor motion time in (66) detailed and simplified. Also, in (66, Pages 46 & 47) a table has been given as basic information for both approaches (appendix D).

The table consists of work-factor values for body members covering a range of distances and weights. Unfortunately the weight factor has not been considered in any practical detail and range in the table. However, when the time values are plotted against distances for different body members (appendix D), a similarity between the plotted curves for similar distances was noted. The plotted curves of work factors firstly against distances and secondly against weights for arm motions have shown that:

The work factor times are almost proportional to the square root of distance and the relation between time and weight could be expressed as

\[(TW)^{68} + 2 = m_1(W + .5)\]

or

\[T = \frac{m_1(W + .5) - 2}{W} \times 1.47 \quad (6.9.)\]

where \(m_1\) is a function of distance. Equation 6.9. has been derived for arm motion only since the weight variation for other members has not been specified in detail. However these relationships could not be directly applied to fabrication assembly. But the proportionality of weights and distances to the times are noticeable. In fabrication assembly, the distance factor depends on the size of a component i.e. when component pieces are relatively large then handling, adjustment and movement around the work piece are more lengthy than when the work piece
is small. Thus it can be concluded that a handling time could also be proportional to the square root of piece size or length \((l^{0.5})\). On the other hand assuming a work piece has a square shape with a side length \(l\), weight \(W\) and thickness \(t\), the side length is: \(l = (\frac{W}{7.8t})^{0.5}\).

The factor \(m_1\) in equation 6.9, which, as already stated, is a function of distance, can be assumed to be proportional to a square root of distance, and distance is proportional to the square root of weight, then factor \(m_1\) can be assumed to be proportional to the fourth root of a work piece weight. It is reasonable to take the largest piece in a component as a measure of distance for assembly time, since the other pieces of the component will have displacements within, or proportional to, this distance. Unfortunately subassemblies which are used to reduce the work, will affect this relation and make it more complex.

However, assembly time is spent in positioning the pieces in relation to each other, thus the number of the pieces in a component is logically another major factor in assembly time. If the displacement of one piece in a certain distance takes, say, \(T\) minutes to be performed, the displacement of \(N\) similar pieces within the same distance will take \(N \times T\) minutes. Usually in practice the smaller pieces are adjusted against the larger ones. Thus the wider the weight distribution in a component, the less the handling time required.

6.8.4. Welding Time

6.8.4.1. Standard Data for Arc Welding

It is said, in section 6.4.2.14, that the amount of weld metal in a fillet weld is proportional to \((\text{weld size})^2\). This is justified in practice by
plotting the weight of weld metal against weld size, using values from Table 2 in Ref. 3 page 6.4.3. (appendix E). On the other hand, tables in Ref. 19 (see appendix E), give the detail of arc time and cleaning time for manual welding as well as CO2 semi-automatic welding. The tables consist of the time values and other processing information for a range of weld size from 3mm up to 25mm.

Studying only the flat and horizontal positions and plotting the times against weld sizes will produce a set of graphs similar to those represented by graphs in figures 6.18 and 19. The graphs have been plotted using values from Ref. 19, tables 5 and 113 respectively. These graphs show that the relationship between time and weld size is not linear. In order to investigate further the nature of the relationship, the values given in the tables have been used in a log-log mode of graphs and the result became promising as is shown by the graphs in figures 6.20 and 21. Studying all of the graphs prepared, by using the values from the tables above-mentioned, in the same manner, the following results are obtained: (appendix E)

1) A general relation between welding time (including arc time and deslagging) and weld size can be expressed as

\[ T_w = m t_w^n \]  \hspace{1cm} (6.10)

where \( T_w \) = time in minutes,
\( t_w \) = leg length
\( m \) = a factor which depends on process detail mainly electrode type and size, position and current.
Figure 6.18- Welding Operation Time (min/m) - Weld size (mm)
Manual Metal Arc welding, Fillet weld with Rutile electrode.
Figure 6.19 - Welding Operation Time (min/m) - Weld size (mm)
Semi-automatic CO2 Welding, Fillet weld, with solid wire 1.2 mm in diameter.
It is not the same for different tables and in manual welding it changes between 0.05 to 0.18 and in semi-automatic CO\(_2\) welding 0.04 to 0.1.

\(n\) = the exponential factor which is about 2 to 2.05 for manual welding and about 1.90 to 1.96 for semi-automatic CO\(_2\) welding.

ii) As is to be expected, manual welding is much more time consuming than CO\(_2\) welding.

iii) There are some exceptions and rapid changes in the time values which do not follow the common trend over the range. These abnormalities are found generally in welds with 8\(\text{mm}\) leg length and less. In some cases the changes are not practically justifiable (see figure 6.19), since for instance there is a decrease in weld time while the leg length has been increased or for the same electrode, same number of passes and for the same weld size, the deslagging time in flat position is significantly less than in the horizontal position. In figure 6.19, the time values for horizontal and flat positions are equal to each other, with the exception for 5\(\text{mm}\) weld size. Whereas for smaller weld sizes the time changes do not follow a normal variation. This equality of time values between flat and horizontal position is also to be found in another table (appendix E table 7).

iv) The values for \(n\) both in horizontal and flat positions are almost the same, whereas \(m\) for horizontal position is generally more than flat position. But as it was already stated, the differences may be changed from one table to another. However, changing from flat position
Figure 6.20: Manual Metal Arc welding. Results from Fig. 6.18 in a log-log mode.
Figure 6.21: Semi-automatic CO2 welding. Results from Fig. 6.19 in a log-log mode.
to the horizontal has a greater effect on time in manual welding. Semi-automatic welding with cored wire is mainly used in site welding in order to provide more protection for a weld in such condition and environment. This was confirmed by the people in B.W.R.I. However, studying tables from (19) (Tables Appendix E) shows that the time variation for welding with cored wire is similar to the welding with bare wire but always higher. No application for cored wire has been observed in the companies' fabrication shops which have been visited.

The final conclusion is that welding time is proportional to almost (weld size)$^2$.

6.8.4.2. Welding Cost Estimates

The graph in figure 6.22 shows the relative costs of full strength 'T' joints for three different edge types. This graph is reproduced from (3). The graph has been replotted in a log-log mode after conversion to metric units in figure 6.22a. Although the values represent the relative costs of three different joint types and are not for general use, they also represent the relative costs of welds based on the plate thicknesses.

Graph 6.22a shows that the three curves are almost parallel to each other; this means that for all three curves the costs are proportional to the same power of weld size. A general equation can be written for all three curves like this:

$$T_w = m t^n + K \quad (6.11)$$

where $m$ and $K$ are constant for every single curve. The best values for
Figure 6.22 - Relative Cost of full-strength welds. Ref.(3)
Relative Cost of full strength welds

FIGURE 6.22a - Relative welding cost.

\* K = 0.4 for square edge, 6.2 for 45° bevelled, and 4.7 for 60° bevelled.
m and K are:

- for square edges: \( m = 0.02 \) \( K = 0.4 \)
- for bevelled edges 45°: \( m = 0.013 \) \( K = 6.2 \)
- for bevelled edges 60°: \( m = 0.0085 \) \( K = 4.7 \)

n could be assumed to be constant for all of them and is approximately \( n = 1.94 \).

t is the plate thickness which is meant to be the thickness of the thinner plate of the parent pieces. When a joint is to be full strength the size of the fillet weld is 0.75 of the plate thickness; \( tw = 0.75t \). For 45° edges \( tw = 0.6t \) and for 60° edges \( tw = 0.53t \) (3), so that for a full strength joint, regarding the above relationships, either of two variables, \( tw \) or \( t \), can be used in the equations. Thus, for square edges, substituting weld size for plate thickness in equation 6.11 we have:

\[
T = m \left( \frac{4}{3} tw \right)^n + K
\]

or

\[
T = 0.02 \left( \frac{4}{3} tw \right)^{1.94} + 0.4
\]

So for square edges \( T = 0.0347 \) \( tw^{1.94} + 0.4 \)

and for 45° edges \( T = 0.0226 \) \( tw^{1.94} + 6.2 \)

for 60° edges \( T = 0.0148 \) \( tw^{1.94} + 4.7 \)

The values of \( m \) and \( K \) should not be considered at this stage since the detail of the process and the cost values have not been specified in (19).
The main deduction to be made from this discussion are that; the value of \( n = 1.94 \) in equation 6.11 is close to what has been found for \( n \) in section 6.8.4.1. equation 6.10 for welding time which has been derived from standard data in (19). Unfortunately the type of welding process for figure 6.22 is not known, since it is just a relative cost consideration between three different types of joints. Therefore a direct comparison with the welding time is not possible. Furthermore, the elements of the process which had been included in these costs have not been given. Consequently equation 6.11 could not be directly applied to a cost or time estimation.

6.9. Synthesis

6.9.1. Assumptions

To establish a general equation for the total operation time of a fabricated component some assumptions were found to be necessary at this stage. The assumptions are to minimise the ancillary complexities of a component and narrow the component variables to the essential ones.

These assumptions are:

i) A component has been constructed of a number of identical pieces 'N', so that the thicknesses are equal as well as the size lengths.

ii) The pieces are to be cut from plates by oxygen cutting machine with one single torch.

iii) The pieces are square shape with no further complexities in shapes.

iv) No extra piece preparation will be involved at this stage. Then processes such as edge preparation, straightening, multi-process of cutting,
bending and forming, etc. will not be required in the manufacturing of the component.

v) Every piece is joined by one of its edges to the next of the pieces.

vi) The joints are either T joint, cruciform or corner joints welded by fillet weld with the same size. The joints are to be continuously welded and are fully accessible. They are welded in flat position.

vii) The welding process is semi-automatic CO₂ welding with solid wire. Proper electrode diameter, current, voltage, feeding speed and the other requirements are selected.

viii) Normal jigs, fixtures, manipulators and handling equipment are available as required.

The use of the above assumptions leads to a component with following detail;

If the number of the pieces is N, with every piece weight \( W_p \)
the component weight is \( W = N \times W_p \). \((a)\)

If the cutting length for each piece be \( l \) then the total cutting length for all of the pieces is \( L = lN \).

On the other hand \( W_p = \left(\frac{l}{I}\right)^2 \times t \times 7.8 \text{ kg} \)
where \( l \) is in metres and \( t \) is the plate thickness in millimetres,

then, \( l = 4 \left( \frac{W_p}{7.8t} \right)^{0.5} \) or \( L = 4N \left( \frac{W_p}{7.8t} \right)^{0.5} \)

From equation \((a)\) \( W_p = \frac{W}{N} \)
then, \( L = 4 \left( \frac{W x N}{7.8t} \right)^{0.5} \)
According to the assumption each piece is joined by one of its legs to the rest of the component. Then the number of the joints is \( N - 1 \) and the total joint length will be:

\[
L_j = (N - 1) \frac{1}{4}
\]

In practice the pieces of a component are not identical. The thicknesses are different as well as the sizes and weights. Main pieces which carry the loads are thicker than, for instance, the stiffeners. Some are bigger and heavier than the others. Some pieces are relatively long and not square. These complexities as well as weld varieties and joint length varieties will be discussed after the development of the basic equation (section 6.10.10 and 11).

6.9.2. Component Operation Time

The operation time of a component, based on the assumptions made in section 6.9.1., consists of cutting, assembly, tacking and welding time. The cutting time of a piece has been given in equations 6.5. and 6.7.

i.e.

\[
T_c \approx 0.04 (t + 46) 1 + 1.64
\]

or

\[
T_c \approx \frac{1}{100} (33Wt)^{0.5} + \left(\frac{2W}{t}\right)^{0.5} + 1.64
\]

Thus for a component made of \( N \) pieces the total cutting time is

\[
T_c \approx N \left[ \frac{1}{100} (33Wt)^{0.5} + \left(\frac{2W}{t}\right)^{0.5} + 2.7^{0.5} \right] \quad (6.12)
\]

or

\[
T_c \approx N \left[ 0.04 (t + 46) 1 + 1.64 \right] \quad (6.13)
\]
The assembly time, though not explicit, one might expect to be proportional to the weight in a relationship similar to equation 6.9., i.e.

\[ T_{ass} = \frac{1}{W} \left[ m_1 (W + 0.5) - 2 \right]^{1.47} \]

So for a component it will be \( T_{ass} = \frac{N}{W} (m_1 (W + 0.5) - 2)^{1.47} \) (6.14)

Referring to equation 6.10 the most common value for arcing time of one metre of weld is;

\[ T_w = 0.046 \, t_w^{1.94} \]

which is for semi-automatic CO₂ welding with solid wire.

Referring to section 2.6.3.7. the time for tack welding can be considered approximately to be 5% of welding time. The ancillary time for CO₂ welding time can be taken as 25% of arcing time (19 pages iv to vi). Then the welding equation is modified by a multiplying factor of 1.3;

\[ T_w = 1.3 \times 0.046 \, t_w^{1.94} \]

or

\[ T_w = 0.06 \, t_w^{1.94} \] (6.15)

For a double sided fillet joint the above time must be multiplied by a factor of 2 and when a component with N pieces is being considered, the total joint length is \((N - 1)l_j\) and the welding time is estimated as follows;
The time for handling and positioning of the component during the welding process has not been considered in the equation. But it should be considered as a part in assembly time because the two operations are similar to each other. Since the equation for assembly time has not yet been prepared, no further modification for the above purpose will be suggested at this stage.

Combining equations for cutting, assembly and welding times will give the total operation time for a fabricated component.

First equations (6.13, 14 and 16) give:

\[
T_{\text{top}} = T_c + T_{\text{ass}} + T_w
\]

\[
T_{\text{top}} = \frac{N}{25} \left[ (t + 46.1 + 41) + \frac{N}{W} \left( m_1 (W + 0.5) - 2 \right) \right]^{1.47} + 0.12(N - 1) l_j t_w^{1.94}
\]  
(6.18)

where \( l_j = \frac{1}{4} \).

In this equation 6 independent variables \( N, t, 1, W, t_w \) and \( m_1 \) are to be determined in order to solve the equation. If the joints are full strength then \( t_w = 0.75t \) and if \( m_1 \) is assumed to be proportional to the piece size \( (1/4) \) then the number of variables will be reduced to 4, that is...
\[ T_{\text{top}} = \frac{N}{25} \left( t + 46 \right) + \frac{N}{W} \left[ K \left( W + 0.5 \right) - 2 \right] 1.47 + 0.017(N-1)t^{1.94} \]  

(6.19)

where \( K \) is a constant.

Again considering equations 6.12, 14 and 17 gives;

\[ T_{\text{top}} = N \left[ \frac{1}{100}(33Wt)^{0.5} + \left( \frac{7W}{t} \right)^{0.5} + 1.64 \right] + \frac{N}{W} \left[ m_1(N + 0.5) - 2 \right] 1.47 + 0.037(N-1)W^{0.5}t^{1.44} \]  

(6.20)

This time, by using the same approach as for equation 6.19, the number of variables will be only three i.e. \( N, W \) and \( t \). Bearing in mind that the piece weights are required in estimating the material cost, the final form of equation 6.20 is simpler than equation 6.19 i.e.

\[ T_{\text{top}} = N \left[ \frac{1}{100}(33Wt)^{0.5} + \left( \frac{7W}{t} \right)^{0.5} + 1.64 \right] + \frac{N}{W} \left[ K \left( W + 0.5 \right) - 2 \right] 1.47 + 0.0246(N-1)W^{0.5}t^{1.44} \]  

(6.21)

where \( K' \) is a constant

6.9.3 Discussion

As one may have noticed the equation, in any form, is cumbersome and, apart from the time required to determine the variables, computation will also be lengthy. Moreover in practice the pieces are not identical and the welds are necessarily all full strength so the \( t_w = 0.75t \) is not valid very often. Therefore in practice one may require to use the equation in a separate form and with different modification factors to compute the three stage operation times for a component. However,
equations 6.18 to 6.21 are believed to be, if not the actual relation between the operation times and the main variables, but the core of such relations, since they comprise the major features and facts of the actual relation. The welding time in particular is the most reliable part of the equation in comparison with the two other parts, since the examination of information from different sources has confirmed the basic relation.

6.9.3.1. Practical Feature of a Component

One of the assumptions made in section 6.9.1. was that in order to simplify the component detail the pieces were assumed to be identical. In practice this is not true. A component is usually made up of a range of pieces having different sizes. This will change the cutting time as well as the other processing times which are estimated based on the current assumptions.

A component in practice consists of a very few number of relatively large pieces, some moderate sizes and a majority of relatively small pieces which, in comparison with the large pieces, are very light. It was felt that these are the dominant feature for the majority of fabricated components, if not for all of them. These features could be found particularly in components where the number of the pieces is more than ten. In other words, as the number of the pieces increases, the pieces sizes are more likely to have the variety just discussed.

One may find a similarity between the piece variety in a component and a "Pareto distribution". The Pareto distribution has been introduced for the distribution of sales per a period of time (65) and also for the
distribution of values between the parts of a device in (60). Here one may accept that in 80% of fabricated components only 20% of pieces have 75% of total weight of component or more than 90% of a component weight is distributed between less than 50% of the pieces.

On the other hand considering a component made of two square pieces with the same thicknesses, and the material volume of $V_1$ and $V_2$ respectively so that

$$V = V_1 + V_2 = \text{Const.} \quad \text{(see the diagram)}$$

If $\frac{V_1}{V_2} = K$ and $K \ll 1$ then

$$V_1 + KV_1 = \text{const.}, \quad \text{or}$$

$$V_1 (1 + K) = \text{const.}$$

Since the cutting length of a piece is proportional to $(\text{volume})^{0.5}$, the cutting length 'L' for these two pieces is

$$L = C(V_1)^{0.5} + C(V_2)^{0.5} \quad \text{or}$$

$$L = CV_1^{0.5} (1 + K^{0.5}) \quad \text{(a)}$$

where $C$ for a particular material and thickness is constant. The joint length 'L_j' is equal to the side length of the smaller piece (see the diagram) i.e.

$$l_j = \frac{C}{4} (V_2)^{0.5} = \frac{C}{4} (KV_1)^{0.5} \quad \text{(b)}$$

Equations (a) and (b) show that both the cutting length and joint length are proportional to $(K)^{0.5}$ so that when $K = K_{\text{max}}$, i.e. the two pieces are identical, then $L = L_{\text{max}}$ and $L_j = l_j_{\text{max}}$, and vice versa, or;

For $K = 1$ $V_1 = V_2 = \frac{V}{2}$, $L = CV_1^{0.5} \times 2 = C(V/2)^{0.5}$ $\times 2 = C(2V)^{0.5}$

$$l_j = \frac{C}{4} (V_1)^{0.5} = \frac{C}{4} (V/2)^{0.5}$$
For $K = 0$, $V_1 = V$, $V_2 = 0,$

\[ L = C V_1^{0.5} = CV^{0.5} \]

\[ l_j = 0 \]

Therefore the weight variety in component pieces, which is similar to Pareto distribution, reduces the fabrication time in comparison with identical pieces. This reducing effect is considered in the next section by studying the companies' data.

6.10 Solution by Applying Companies' Data

6.10.1. Initial Study

After collecting the required information from companies' data, an experience of applying the recent equations (section 6.9.2.) was carried out. The results of operation times estimated from the equations were compared with the times allocated by the companies. The comparisons were found to be unsuccessful. The time differences could not be interpreted. The only result was that all of the times estimated from the equations were much less than the times estimated by the companies, but the differences were not in the same ratio. Some comparative evaluation between the components from the same company has showed that their allocated time could not be accurate. This has been appreciated by the company's people, but since in most of the cases the company planned times had not been produced in proper detail the reasons for the differences could not be found.

However, an attempt to adjust the equations against the planned times did not come to a good result, since an adjustment could fit approximately
to the planned times from one company, was found unsuitable for another company.

6.10.2. The Planned Times against Components' Variables

The next attempt was to plot planned times by companies against every single variable and after that against simple combinations of variables. The most promising result came firstly from the relation between planned time and the component weight 'W' in a log-log mode. The relation between total operation times from the companies' plannings and the total component weights are shown in figure 6.23. This graph has been produced for 58 separate fabrications from four different companies. The scatter of the points was found to be much wider than what was expected.

6.10.3. Companies Comparison

It was noticed that there are some similarities between components from two different companies (Groups 2 and 3). But when the operation times from their plannings were compared with each other, the differences were found to be significant. Figure 6.24 shows the planned time against weight for components from the two companies. There is a significant difference between them in general no matter whether the components are similar or not. In a third attempt another variable, number of pieces N was introduced. This time the components plannings from the two companies were plotted against the product of weight 'W' and the number of the pieces (N x W) in a log-log mode. Figure 6.25 shows the similarity between the general trends of the two groups, while they are more separate from each other. Comparing figure 6.24 with figure 6.25 shows the positive effect of N and how accumulated the scatters of each separate group. The
FIGURE 6.23: Fabrication Time - Component Weight.

The times are planned by the companies.
FIGURE 6.24: Fabrication Time - Component Weight for Group 2 and 3. The times are planned by the companies.
FIGURE 6.25: Fabrication Time - Component Weight x Number of Pieces (W x N) for Group 2 (or B) and 3 (or C).
FIGURE 6.26: Fabrication Time - Component Weight x Number of Pieces (W x N) for the four groups.
relation between planned time and $W \times N$ for four groups has been shown in figure 6.26. The groups are quite separated from each other. The effect of $N$ on the two other groups is similar to that for the first two groups.

6.10.4. Deductions

Further study of figures 6.23 to 6.26 leads to the following tentative deductions:-

i) There are some differences between the operation times allocated by different companies so that they should not be considered together.

ii) No attempt should be made to create a single equation to fit all the companies' time together. Then the failure of the previous attempts is justified.

iii) Although the planning for every individual component may not be reliable, in general the similarity between the group patterns shows that there is some relationship between all of them. In other words, the actual relation between the times and variables can be represented in an equation that is applicable to all of the companies' planned times albeit with some adjustment.

iv) Component weight $W$ and the number of pieces $N$ are two major component variables that the operation times are related to in some way.

v) There should be some reasons for the general differences between the companies' planned times.

6.10.5. Planned Times Differences

The companies have different approaches to converting the time estimated
to the actual labour cost, this depending upon whether they consider
the labour overhead at this stage or not. The lowest times, belonging to
the actual labour cost, this depending upon whether they consider
group (2) were found to be estimated based on direct labour times
which had been studied in the shop from time to time. The companies
with relatively higher times are where the workers are paid according to
either piece work or bonus. In other words, the lower time group is
closer to the running time rather than the actual labour time.
Consequently, if all of these companies are producing and selling their
product to the same market with more or less the same percentage of
benefit, then the actual cost of similar components in different
companies should be similar at the final cost estimation stage. This
means that in order to end with similar cost they should have used
different multiplication factors in the final estimation. The factor
is affected in a different way by labour overhead factor, duty cycle
factor in the shop and the shop efficiency.

One minor parameter which causes the time differences between various
shops is the general accuracy of the products. It has been noted that
similar components in different shops are not being produced to the
same accuracy, because of the particular requirements. For instance, in
one company the straightness of all of the relatively large pieces were
checked before assembly stage. Also the accuracy of section edges cut
by a cropper could not satisfy the requirement so they used a disc saw
for this purpose. Whereas in another shop, the piece straightness was
not checked and the sections were part off by a cropper. The
general welding process in a shop whether it is semi-automatic or manual
also affects the manufacturing time, as do the other general major
complexities and features of the component.

6.10.6. Adjustment
In order to be able to study all of the components from the four different companies together, adjusting factors have been used. The factors were to change the position of the group patterns to make them relatively align with each other. The effect of this adjustment is shown in figure 6.27 where, in comparison with figure 6.23, the width of the scatter has been reduced significantly. But the proper values for the factors could not be specified at this stage, since a basic relation is not yet known.

6.10.7. First Guide for Designers
Apart from the basic relation between component weight and the operation time, which was already pointed out, a designer can at this stage have a rough estimation of operation time, using only two variables, W and N. Plotting the operation times against N x W for the components which have already been produced in the shop and timed could be useful. Such a graph will be a band of components' times similar to each of the groups shown in figures 6.24 or 6.25. Certainly, such a graph should be produced in log-log mode. This graph will be more useful if the components were chosen from the same family, with the same level of complexities and same welding process. Furthermore, the component made of plates is preferred not to be mixed up with components made of sections.

6.10.8. Development of the Equations
It was noticed that most of the companies' planned times have not
separated the assembly times from welding times. Therefore it was decided to develop an equation for both times at once, which we shall call joining time. To develop an equation for joining time based on the companies' data, the main facts from the previous investigations were accepted as a guideline for the purpose. These facts will be explained within the next few sub-sections.

It was shown in section 6.8.4. that there is a significant difference between welding time for semi-automatic CO₂ welding and manual welding. Thus, these two have been considered separately.

6.10.8.1. Component Weight instead of Piece Weight

It was mentioned earlier that the solution must be as brief as possible and easy to use. Therefore a solution which requires the estimation of the processing time for each single piece of a component separately is not suitable for a designer need by any means. This argument enforces the choice of parameters for the solution, to be easy to determine i.e. parameters of individual pieces are not good for the purpose. Instead, if possible, the variables should be selected from the general component parameters. Consequently it was decided to choose the component weight \( W \) as one of the possible variables rather than the piece weights, so that;

\[
W = N \times W_p \text{ (average)}
\]

where \( W_p \) (average) is the average piece weight in a particular component.
6.10.8.2. Assembly Time

The discussion and equation 6.9. in section 6.8.3.2. show that the main variables in the assembly time are the weight of the pieces and the displacements.

\[ T_{ass} = \frac{(m_1(W_p + 0.5) - 2)^{1.47}}{W_p} = \frac{(m_1W_p + 0.5m_1 - 2)^{1.47}}{W_p} \]

The most important part of this equation is the first term where the weight \( W_p \) has the maximum value, i.e. \( \frac{(m_1 W_p)^{1.47}}{W_p} = m_1^{1.47} \times W_p^{0.47} \).

Therefore one can conclude that the assembly time in relation with weight is mainly proportional to \( W_p^{0.47} \) and for \( N \) number of pieces it is \( N \times W_p^{0.47} = N \times (\frac{W_p}{N})^{0.47} = N^{0.53} \times W_p^{0.47} \). Consequently \( N^{0.53} \) and \( W^{0.47} \) can be taken as two terms of the equation that one may start with to develop for estimating assembly time and one should expect that the final values for the two exponents of \( N \) and \( W \) will not be too far away from 0.53 and 0.47 respectively.

6.10.8.3. Welding Time

The general equation for welding time based on "standard data" (19) was derived in section 6.8.4.1. equation 6.10 which is:

\[ T_w = m t_w^n \]

where for "MMA" welding \( m = 0.05 \) to 0.18 and \( n = 2 \) to 2.05, and for semi-automatic \( CO_2 \) welding \( m = 0.04 \) to 0.1 and \( n = 1.90 \) to 1.96.

Also it has already been explained that the weld volume for a joint is
proportional to $t_w^2$ and a similar relationship can be expected between arcing time and the weld size (section 6.4.2.14).

Finally in section 6.8.4.2., equation 6.11 has been derived for different T joints which is

$$T_w = m t_w^n + K$$

where for all three different joints $n = 1.94$.

All of these relationships show that, firstly, welding time is proportional to $t_w^n$ where $n \approx 2$, secondly, welding time for "MMA" welding is usually greater than that for CO2 welding, so that for MMA, $n$ can be slightly more than 2 whilst for CO2 welding it is less than 2. Also factor $m$ for "MMA" is expected to be much greater than that for CO2 welding. Re-arranging the general equation for welding time, for a component made of $N$ pieces with $(N-1)$ joints of $l_j$ length, will make the equation as follows:

$$T_w = (N-1)l_j \times m t_w^n + K$$  \hspace{1cm} (a)$$

and weld size

where $l_j$ and $t_w$ are taken as average joint length for a piece with average weight $W_p$. Thus $l_j$ is proportional to $\left(\frac{W_p}{t}\right)^{0.5}$ or $\left(\frac{W_p}{t_w}\right)^{0.5}$

and the equation (a) will become;

$$T_w = \text{fx} \ (N-1)\left(\frac{W_p}{t_w}\right)^{0.5} x t_w^n + K = \text{fx} \ (N-1)(W_p)^{0.5} x t_w^{n-0.5} + K$$
where \( f \) is a constant factor. Substituting \( W_p = \frac{W}{N} \) and taking \( n = 2 \) the equation will become;

\[
T_w = f \times \frac{N-1}{N^{0.5}} \times W^{0.5} \times t_w^{1.5} + K'
\]

When the number of pieces in a component is relatively high \( N-1 \approx N \) so that the equation will become

either

\[
T_w = f \times N^{0.5} \times W^{0.5} \times t_w^{1.5} + K'
\]

or

\[
T_w = f \times (N-1)^{0.5} \times W^{0.5} \times t_w^{1.5} + K'
\]

Consequently the last two equations give an initial idea and a starting point to develop an equation for welding time. Similar to the discussion in section 6.10.8.2, the three exponents for the variables \( N, W \) and \( t_w \) are expected to be not too far beyond the values in equation (b).

6.10.8.4. General Effect of \( W \) and \( N \) on the Joining Time

The relation between planned times and \( W \times N \) for the companies' components (figure 6.25 section 6.10.3) shows that the total operation time is proportional to \( (W \times N)^b \) or \( W^{b_1} \times N^{b_2} \), so that \( b \) for all of the four groups of components is less than unity. The general equation between operation time and these two variables can be written as:

\[
T = W^{b_1} \times N^{b_2} \times f
\]

or

\[
\log T = b_1 \times \log W + b_2 \times \log N + \log f
\]
Using "least square" method to find the net regression coefficients of this equation i.e. $b_1$ and $b_2$ and constant $f$ (43) will come to the following results for the four different groups of companies' data:

<table>
<thead>
<tr>
<th>Group</th>
<th>No. of Components</th>
<th>$T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5</td>
<td>$26.3 \times W^{0.56} \times N^{0.71}$</td>
</tr>
<tr>
<td>2</td>
<td>19</td>
<td>$4.39 \times W^{0.4} \times N^{0.71}$</td>
</tr>
<tr>
<td>3</td>
<td>18</td>
<td>$15.22 \times W^{0.53} \times N^{0.38}$</td>
</tr>
<tr>
<td>4</td>
<td>13</td>
<td>$24.82 \times W^{0.47} \times N^{0.78}$</td>
</tr>
</tbody>
</table>

Although the above results show no close similarity between the coefficients for different groups, the values for the exponents can be reasonably accepted as approximate limits for the actual values. The exponents for the weights in particular are quite noticeable since the range is only from 0.4 to 0.56.

One reason for the wide range of the multiplication factors is because of the general differences between the planned times for different companies, which was discussed earlier in section 6.10.5. Another reason particularly for the first group is that the number of samples for this group is only 5 so that the coefficients are very sensitive to any inaccuracy of the planned time. Further discussion is given in section 6.10.9.

6.10.8.5. Discussion and Deduction

Since the analytical approach did not lead to a proper equation for the purpose, it was decided to use the guide points mentioned earlier in section 6.10.8.1 to 4, as the initial basis to develop an equation by
applying companies' data.

To achieve an equation for joining time, a reconciliation between the companies' planned time and the analytical basis by using a trial and error approach was carried out. During this attempt many different combinations of all possible variables have been tried, but only three main variables were found to have significant effect on the joining time i.e. component weight $W$, number of pieces $N$ and the weld size $t_w$. Later on it was noticed that in order to achieve sufficient accuracy in the result, it becomes necessary to introduce a new parameter which represents the particular weld feature of the component (section 6.10.11).

The two equations which have been found to be the most suitable for all of the components are;

1. For semi-automatic CO$_2$ welding

$$T_w = W^{0.48} (N^{32} + 8 + 0.09 t_w^{1.5}) (N - 1.6)^{5} x F_w x K_1 \quad (6.22)$$

2. For manual welding

$$T_w = W^{0.48} (N^{32} + 10 + 0.2 t_w^{1.6}) (N - 1.6)^{4} F_w x K_2 \quad (6.23)$$

where;

$T_w$ = Total operation time (Minute) for welding and assembly

$W$ = Component weight in kg

$N$ = Number of pieces

$t_w$ = weld size or leg length of the weld in millimetres
\[ F_w = \text{weld factor, will be discussed in section 6.10.11} \]
\[ K_1 & K_2 = \text{constants to be specified for any particular shop, depending on the labour efficiency (19), shop facilities and the batch quantity.} \]

6.10.9. The Key Process

To find an equation for piece preparation time requires a consideration of more variables such as the piece sizes and the other detail. Therefore an attempt was made to try to find a relation between the time for piece preparation and the joining process. From the planned times the total operation times, welding and assembly times, and the piece preparation times have been plotted against component weight separately and for each individual group. Figures 6.28 to 6.31 show the relationships produced in a log-log mode. From these graphs the following deductions may be made:

1) The welding and assembly times follow almost the same pattern as the total operation times. Whereas the pattern of cutting times are different.

2) The welding and assembly times, in comparison with piece preparation times are much closer to the total operation times. This means it is reasonable to accept that joining times are the key processes in a fabrication. This was predictable but not in such a significant way.

3) The pattern of welding and assembly times becomes closer to the total operation times as the times become greater and greater.

4) For the components with joints other than squared edges the patterns are not so close as for components with square edges (see figure...
FIGURE 6.28: Fabrication, Welding and Piece preparation Times against Component Weight for Group 1.
FIGURE 6.29: Fabrication, Welding and Piece preparation

Times against Component Weight for Group 2.
FIGURE 6.30: Fabrication, Welding and Piece preparation
Times against Component Weight for Group 3.
FIGURE 6.31: Fabrication, Welding and Piece preparation
Times against Component Weight for Group 4.
That is because edge preparation has been added to the piece preparation times. Edge preparations relatively reduce the weld sizes and increase the cutting times.

Moreover the general relation is disturbed, particularly when either the component weight is less than 40 kg and the number of the pieces is less than 10 or when piece preparations required considerable extra processes such as bendings. One important reason is that the lighter and smaller the component the more significant becomes the piece preparation time (see also ii).

The total planned times were plotted against welding and assembly times. Figure 6.32 shows the relationship plotted in a log-log mode. But when the piece preparation times are plotted against assembly and welding times the result shows that there is not such a good relationship, see figure 6.33. Consequently it is considered that the smoothness of the relationship in figure 6.32 is due to the significance of the joining time compared with the piece preparation time. Since the relationship between total operation time and joining time, and between joining and piece preparation time had been plotted in a log-log mode (figures 6.32 and 6.33), one can express the approximate relation as:

\[ T_C \approx A T_w^{x1} \tag{6.24} \]

where \( T_C \) = piece preparation times in minutes

\( T_w \) = joining times in minutes.

Using "least square" method to calculate the regression coefficients for
FIGURE 6.32: Fabrication, Joining and Piece preparation Times against Joining Time for four Groups.
FIGURE 6.33: Fabrication, Piece preparation Time against Joining Time for four Groups.
each group separately gives the results as follows:

<table>
<thead>
<tr>
<th>Group</th>
<th>A</th>
<th>$x_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group 1</td>
<td>0.81</td>
<td>0.96</td>
</tr>
<tr>
<td>Group 2</td>
<td>1.33</td>
<td>0.69</td>
</tr>
<tr>
<td>Group 3</td>
<td>2.96</td>
<td>0.69</td>
</tr>
<tr>
<td>Group 4</td>
<td>1.95</td>
<td>0.7</td>
</tr>
</tbody>
</table>

"$x_1$" and "A" are two factors which are constant for each group. The values for A and $x_1$ for the first group are quite different from the three other groups. Because all of the components in this group have to be edge prepared, i.e. the edges are not squared. Furthermore, since the number of the components in this group is very few, only 5, any inaccuracy in the time values even for one single component can affect the factors A and $x_1$ dramatically. For instance, all of the components in this group have similar configuration and detail, whilst the ratio $\frac{\log (T_w)}{\log (T_c)}$ for component 2 is quite different with the four others.

Comparing the joining time of this component with all other components (figures 6.28 to 31) shows that in general as the component becomes lighter and smaller the joining time becomes closer to the piece preparation time whilst for this component in its own group it does not follow the argument just mentioned. If it did, group 1 would have a similar value for $x_1$ as the other three groups, whilst A would increase significantly.

The values of $x_1$ for groups 2, 3 and 4 are close to each other, whilst A's are not. This means that the increase of the time for the groups
are similar, but either production or shop feature for each individual group causes different factor $A$; Group 2 has the minimum $A$ between these three groups since the batch quantity "$Q" for this group is much higher than the other two groups (section 5.2, 6.12.2 and 2.4.2). Moreover, the accuracy of piece preparation in group 3, with maximum $A$, is higher than in groups 2 and 4 since the control of straightness of pieces is a general extra feature for this group i.e. the general accuracy is higher.

These are the reasons which explain the differences; there might be some other reasons related to the shop features or the estimators' approaches in different companies, and these reasons could not be explicitly specified.

6.10.10. Total Operation Time

Considering equation 6.24 in section 6.10.9, one may expect the equation for total operation time to be as follows:

$$T_{top} = T_w + A_1 T_{w}^{x_1}$$

(a)

But the scatter in the relationship between joining and piece preparation times in figure 6.33 shows that the equation (a) is not complete yet. The piece preparation time may be affected by extra processes such as bending, edge preparation, large inside cuts, hand burn and so on. Therefore the second term in equation (a) should be modified by the effect of these extra processes which can be represented in the equation by a piece complexity factor. These complexities, as it will be discussed
are similar, but either production or shop feature for each individual group causes different factor $A$; Group 2 has the minimum $A$ between these three groups since the batch quantity "Q" for this group is much higher than the other two groups (section 5.2, 6.12.2 and 2.4.2). Moreover, the accuracy of piece preparation in group 3, with maximum $A$, is higher than in groups 2 and 4 since the control of straightness of pieces is a general extra feature for this group i.e. the general accuracy is higher.

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later on, will increase the piece preparation time while having some side effects on jointing.

A reconciliation between the above discussion, equation (a), the value of \( x_1 \) particularly for groups 2, 3 and 4 in section 6.10.9 which is \( x_1 \approx 0.7 \) and the experience on the all planned times for four groups comes finally to the following equation;

\[
T_{top} = (T'_w (1 + 0.5 F_{cb}) + 1.4 F_{cb} T_w^{0.7}) 0.23 \quad (6.25)
\]

where \( T'_w \) is estimated from equation 6.22 and 23 and is

\[
T'_w = T_w/K \quad (6.26)
\]

Then for semi-automatic CO\(_2\) welding

\[
T'_w = F_w (N^{0.32} + 8 + 0.09 t_w^{1.5})(N - 1.6)^{0.5} x w^{0.48} \quad (6.27)
\]

and MMA welding

\[
T'_w = F_w (N^{0.32} + 1 + 0.2 t_w^{1.6})(N - 1.6^{0.4} x w^{0.48} \quad (6.28)
\]

Factor 0.23 in equation 6.25 can be taken as a general adapting factor \( F_a \) which should be adjusted based on every particular company costing system (section 6.10.3 to 6.10.6).
6.10.11. Piece Complexity Factor $F_{cb}$

This factor depends on the number of complexities in the pieces that require extra piece preparation processes such as bends, extra hand burns, large inside cuts, edge preparations and so on.

If each extra process increases the number of piece preparation processes by one it can be said that the number of the pieces for this stage has been increased from $N$ to $N + 1$ and for $N_{cb}$ number of complexities it will be $N + N_{cb}$. Therefore if we assume that usually the main pieces in a component may require extra process then the piece complexity factor can be estimated by:

$$F_{cb} = \frac{N + N_{cb}}{N} \quad (6.29)$$

where $N_{cb}$ is the number of bends or edge preparation and the like. It has been assumed that piece complexities are those which can be produced with proper equipment in the shop. In using equation 6.29 any unusual complexity where the process is not part of general shop routine should be considered with the appropriate weightage depending on the difficulties involved. Awkward manual processes such as blacksmithing are also considered as unusual complexities. In contrast if a complexity in comparison with the whole component is a minute feature it can be ignored. Therefore a bend in a small piece in a component or a bend which does not contribute in the joints is considered as $\frac{1}{2}$ to $\frac{1}{3}$ of the piece complexity.
6.10.12. Welding Factor $F_w$

This factor depends on the joining features of a component. The proper value for $F_w$ should be chosen by careful study of the component drawing. These features affect the joining time of a particular component in three different ways;

1) Relative increase or decrease of the joint length
2) Either difficulty or ease of positioning which affects the assembly time
3) Special care or accuracy in the weld quality.

To achieve a proper value of $F_w$ for a particular component several features need to be controlled. It requires a good understanding of joining (assembly and welding) difficulties, the effect of the factor $F_w$ as well as the other variables in the time equation, and in general some experience.

6.10.12.1. Fabrication Features affecting Joint Length

Either simple or complex, long pieces or square, continuous or intermittent, single or double side welds, plate or sections, even or uneven distribution of weight are features that affect the joint length in a particular component.

6.10.12.2. A Normal Component

A component is assumed to be a normal if it is made of plate, pieces are welded on one side some of them by two and some by three edges, the pieces may be double side welded only if, either they are joined by one
Weight distribution between pieces is normal (section 6.9.3.1.). The component has no special difficulties in assembly such as in positioning, fit up or set up the pieces and/or not a high accuracy is expected. Figures 6.34 to 6.36 show some examples of normal components. The welding factor for this type of components is $F_w = 1$. Moreover these types of component are not made of long and narrow members. The details of a normal component just mentioned are to be considered as the general and main features of a component.

6.10.12.3. Double side joint effect

Apart from the pieces welded in component by one edge or by short edges end to end, if the main pieces in a component made of plate have double side welds the welding time will increase by as much as twice that of the same component with single side welds, but the handling and assembly time will not change significantly.

6.10.12.4. Plates - Sections

When a component is made of structural sections, with relatively long members welded end to end, the welding time as well as the whole fabrication time will be less than if it was made of plates with the same weight, number of pieces and weld size. Pieces made of sections have usually one or two end cuts whilst plate pieces should be entirely cut out. Ease of positioning and set up as well as relatively short length joints are other common parameters in reducing the processing time for this type of component. Indeed short run welds are the only time...
Figure 6.34: Example of normal component
Figure 6.35: An example for normal component
Figure 6.36: A typical example of normal components
Comparing different type of material sections in this group of fabrications, components made of hollow sections have the highest time consumption whilst components made of light angles or narrow flat bars have the lowest.

From the study of different companies' planned times, it was noticed that the time effect of this feature is not being considered with the same seriousness and some companies take it more seriously than others. It depends on their experience as well as the general accuracy for the different types of components in a shop. Figures 6.37 and 6.38 show two different types of components made of structural sections.

6.10.12.5. Edges and Joints

Compared with the normal component explained in section 6.10.12.2, some of the components are made of pieces mostly joined to each other by three or even four edges. In other words the pieces are mainly surrounded by each other having relatively long and continuous welds. This feature can be found in complex components with either relatively large pieces or high strength. Figure 6.39 is an example of this type of component.

Another type of component in the same category is the one that has either narrow and long members, longitudinally joined, or relatively large circular joints. Figure 6.40 is a typical component having this feature.
Figure 6.37: A typical example of Components made of sections
Figure 6.38: A typical example of components made of sections
Figure 6.39: A complex component
Figure 6.40 A component with different joining features
6.10.12.6. Intermittent Welds

When most of the joints in a component are one sided, intermittent welds with fairly short lengths, the welding time will be relatively less than continuously welded joints. The welding factor in this case depends on the ratio between the length of the runs to the length of the intervals. The welding time is reduced for two different reasons. Firstly, the joint length has been reduced and, secondly, since the joint is not under a serious load it will be treated by a welder as an unimportant joint so that he can weld it with higher current and an electrode which is suitable for high speed welding and low penetration. Non-important joints of this type are a feature that can be easily realised while a component is being designed. In such cases the designer may not specify even the length of the welds and neither does the welder.

A double side intermittent weld can be considered almost as a single side continuous weld if the run and interval difference is not too much.

6.10.12.7. Piece size

A component's pieces are usually not identical. The weight distribution in a component has been discussed in section 6.9.3.1. But in some components the weight distribution may be extremely wide and uneven. They may be made up of one or two relatively heavy pieces and a number of very small pieces. The joints are relatively very short and since during assembly the light pieces are easily adjusted against the larger pieces, the whole joining time (assembly and welding) is relatively short. The welding factor for such a component should be less than
unity depending on the weight abnormality. Figure 6.41 shows a typical example of this kind.

Following the discussion in section 6.9.3.1., components with such features are not very common.

6.10.12.8. Complexity and Simplicity in Assembly

Some of the component features which can reduce the assembly time by ease of positioning were discussed in section 6.10.12.4 and 7. Unusual position of pieces while the component is not so complex, or special accuracy in alignment of pieces and the like can increase assembly times particularly when the batch quantity does not permit designing special jigs. The assembly time for one off products increases rapidly with the complexity in the assembly.

6.10.12.9. Critical Joints

When the joint quality in a fabrication is important, special care is required in welding process. Deep penetration electrode with lower current and/or lower speed of welding is required to produce a sound weld. The assembly time will not change but the welding time increases.

6.10.12.10. Welding Factor Values

According to the different features affecting joining time of a fabrication, and based on the experience on the components' information available, the most practical values for welding factor $F_w$ were established. Table 6.4. shows the values for $F_w$ for different main
Figure 6.41: A typical example of components with abnormal weight distribution.
<table>
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<tr>
<th>Description</th>
<th>Average Value $F_w$</th>
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<tr>
<td>Relatively long continuous joints or combination of closed and open boxes</td>
<td>1.3</td>
</tr>
<tr>
<td>Double side welds (not in short length or one end joints)</td>
<td>1.3</td>
</tr>
<tr>
<td>Positioning difficulties and premachining fab. (especially in one off products or in simple components i.e. $N &lt; 10$)</td>
<td>1.2</td>
</tr>
<tr>
<td>Components with: end to end or one end double side joints, double side intermittent (not very long intervals), no difficulties in assembly, moderate joint lengths, combination of one and two free edges pieces, no special care of joints are called common fabrication</td>
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<tr>
<td>Ease of positioning in relatively complex component i.e. $N &gt; 10$</td>
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<tr>
<td>Abnormal weight distribution when 10% of the pieces make more than 90% of the component weight</td>
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<tr>
<td>Intermittent weld single side</td>
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<tr>
<td>Sections joined end to end R.H.S. &amp; H ,I,T,[</td>
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<tr>
<td>Angles and narrow flat bars</td>
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features of a fabrication component.

Since most of the complex components have a combination of different features the values should be chosen proportional to the importance of each feature for a particular component. The maximum values cannot be used unless the feature is dominant in the component. On the other hand studying every single piece separately in a component to evaluate a proper value for welding factor is wrong since it will be complicated, lengthy and unnecessary.

6.10.12.11. Examples for the Estimation of Welding Factor

To find a proper value of welding factor for a particular component, two approaches are suggested. The first one is to choose the factors for the different features separately and multiply them by each other to find the final welding factor for the component; this approach takes time. The second approach is to take the values in the table as a guide line to choose a proper factor based on the different features of the component. This approach requires some experience and careful consideration of the component drawing.

Example 1: In many cases the features exist partially in a component. For instance, component in figure 6.40 has long joints, partially double side welded while 15 pieces are relatively very small and create, partially, an abnormal weight distribution. Based on these three major features the weld factor is:
Example 2: Intermittent Welds. Components made of large thin plate have usually long or double side intermittent joints. As it was mentioned, in such cases the ease of welding and the actual length of the welds in comparison with the joint length bring the welding factor back to normal such as component (Figure 6.36).

On the other hand component in figure 6.42 which is a simple one, the pieces can be considered to be joined by one end (edge), thus if the welds were continuous and the joint length on the piece 4 was not so short the welding factor was 1. But relatively short welds have reduced it to \( F_w = 0.9 \).

Example 3: Complex Component. Figure 6.39 shows a complex component in which most of the pieces are surrounded by continuous, single or double side welds. The positioning and assembly is also very difficult especially in a one-off production. Therefore the weld factor for this component is:

\[
F_w = 1.3 \times 1.1 \times 1.1 = 1.6
\]
Figure 6.42: A component with intermittent weld
(example 2)
6.10.12.12. Discussion

One may have noticed that the welding factors given in Table 6.4. are influenced by the conditions in any particular shop, so there may be some variation on the values depending on the shop conditions. A designer should bear in mind the flexibility of those factors and adjust the values as required by the particular circumstance involved. The main parameter which affects the shop condition is the batch quantity which in turn affects the values of welding factors. Another important parameter is the general accuracy of the product in the shop.

6.10.13. Piece Complexities Interact Welding Time

During the investigation on the development of the operation time equation, it was noticed that the accuracy of the results from the fabrication time equation (equation 6.25) is much better than the results from the welding time equations (6.22 and 23). Whereas the fabrication time equation has been derived from the welding time equation, and made sensible by introducing the piece complexity factor Fcb. When components are simple and light the differences become more significant. Further study has shown that the piece complexity factor has some side effects on the welding time so that it improves the results from the welding equation. The reason for this side effect can be interpreted as follows:

A simple hypothetical component is considered. It is made of two pieces with a bend as a piece complexity like the one shown in the diagram. The
same component can also be made of three pieces with no bend, having a weld complexity of three weld junctions which in the first component is substituted by a bend. Therefore the component shown in the diagram is partially like a simple component made of three pieces while from the assembly point of view it has almost a two piece component feature. Consequently changing from two pieces to one piece plus a bend does not usually eliminate the total feature of the extra piece. In equation 6.25 the term $0.5 \times F_{cb} \times T_w$ partially belongs to welding time and partially to cutting time. Whereas in the case of edge preparation the piece complexity has relatively small effect on joining time, that is on piece positioning time. Instead, in this case, the ratio of a piece preparation time to the welding time is much higher, so that the term $0.5F_{cb}T_w$ in equation 6.25 belongs mostly to piece preparation times. The interaction of $F_{cb}$ on $T_w$ becomes more significant for light and small components because piece preparation time is more significant for this type of components. This has already been pointed out in section 6.10.9.2 and 5).


The weld sizes in a component are not usually identical ($t_w$). Generally a variety of up to three different weld sizes is feasible. In many cases it is easy to determine the weld size to apply in the time equation by considering the most common and effective weld size in a particular component. But whenever it was difficult to judge in this way, a proper value for $t_w$ to be applied in equations 6.27 or 6.28 can be estimated by an equation;

$$t_w = \left( \frac{\sum_{i=1}^{2} t_{wi}}{N - 1} \right)^{0.5}$$

$i = 1$ to $N$ (6.30)
twi is the sum of the square of the weld sizes of all of the joints in a component. This equation is based on the previous discussion that the welding time was proved to be proportional to \( t_w^2 \) (see section 6.10.8.3.)

6.10.15. The Results of the Time Equation for the Components Available

The final equations for time estimation (equations 6.25, 27 and 28) have been applied to all of the components from four different companies using proper complexity factors and the adapting factors. The equations are reproduced here for convenience.

\[
T_{top} = (T_w^*) (1 + 0.5 Fcb) + 1.4 Fcb T_w^{0.7} 0.23 x F_a
\]

where \( T_w^* \) for semi-automatic CO2 welding is

\[
T_w^* = F_w (N^{0.32} + 8 + 0.09 t_w^{1.5}) (N - 1.6)^{0.5} x W^{0.48}
\]

and for manual welding "MMA" is

\[
T_w^* = F_w (N^{0.32} + 10 + 0.2 t_w^{1.6}) (N - 1.6)^{0.4} x W^{0.48}
\]

The components' parameters, the planned times and the results from the equations have been given in Table 6.5. The results have also been plotted against the planned times. Figure 6.43 shows the relation in a log-log mode.

One may have noticed that the swinging of the results for some of the
Figure 6.43: Planned time against calculated time for four groups.

For Group (A) $F_a = 5.43$
Group (B) $F_a = 1$
Group (C) $F_a = 3$
Group (D) $F_a = 9.35$
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<td>1644</td>
<td>1760</td>
</tr>
<tr>
<td>C17</td>
<td>557</td>
<td>64</td>
<td>4</td>
<td>1</td>
<td>1.03</td>
<td>1964</td>
<td>1728</td>
</tr>
<tr>
<td>C18</td>
<td>503</td>
<td>7</td>
<td>8</td>
<td>.9</td>
<td>1.3</td>
<td>818</td>
<td>805</td>
</tr>
<tr>
<td>C19</td>
<td>1825</td>
<td>100</td>
<td>6.5</td>
<td>1.6</td>
<td>1.2</td>
<td>29776</td>
<td>17290</td>
</tr>
<tr>
<td>D1</td>
<td>1475</td>
<td>58</td>
<td>7</td>
<td>1.6</td>
<td>1.17</td>
<td>19550</td>
<td>20874</td>
</tr>
<tr>
<td>D2</td>
<td>215</td>
<td>89</td>
<td>3</td>
<td>1.6</td>
<td>1.1</td>
<td>9110</td>
<td>13580</td>
</tr>
<tr>
<td>D3</td>
<td>11</td>
<td>12</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>431</td>
<td>373</td>
</tr>
<tr>
<td>D4</td>
<td>1480</td>
<td>165</td>
<td>6.5</td>
<td>1.6</td>
<td>1.18</td>
<td>35267</td>
<td>39290</td>
</tr>
<tr>
<td>D5</td>
<td>970</td>
<td>63</td>
<td>10</td>
<td>1.6</td>
<td>1.2</td>
<td>18502</td>
<td>18756</td>
</tr>
<tr>
<td>D6</td>
<td>1.5</td>
<td>4</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>84</td>
<td>98</td>
</tr>
<tr>
<td>D7</td>
<td>3</td>
<td>4</td>
<td>3</td>
<td>.9</td>
<td>1.25</td>
<td>117</td>
<td>110</td>
</tr>
<tr>
<td>D8</td>
<td>3.5</td>
<td>2</td>
<td>8</td>
<td>1.1</td>
<td>1</td>
<td>66</td>
<td>71</td>
</tr>
<tr>
<td>D9</td>
<td>1.3</td>
<td>3</td>
<td>4</td>
<td>1</td>
<td>2</td>
<td>96</td>
<td>94</td>
</tr>
<tr>
<td>D10</td>
<td>12</td>
<td>5</td>
<td>8</td>
<td>1</td>
<td>1</td>
<td>130</td>
<td>116</td>
</tr>
<tr>
<td>D11</td>
<td>20</td>
<td>18</td>
<td>6</td>
<td>1.2</td>
<td>1.15</td>
<td>983</td>
<td>944</td>
</tr>
<tr>
<td>D12</td>
<td>12</td>
<td>7</td>
<td>3</td>
<td>1.3</td>
<td>1.5</td>
<td>503</td>
<td>548</td>
</tr>
</tbody>
</table>

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companies and especially in some components is fairly wide. In some cases it is not possible to justify the deviations. But generally one can come to this argument that the human effects on the processing time is one of the major parameters for these wide deviations. From time to time the estimators have to change the specified times for different components and these amendments are based on the feedback from shop. At first they specify the processing time based on their experience and the previous planned time for similar components. Now if the fabricators' wages are based on daily work, the specified times are checked by estimators from time to time. The correction or amendment is usually required which is not only because of the estimator's errors but, in many cases, because of the operation factors which depend on the labour ability and skill, choice of electrode type and size, current and the like. In one of the companies the welder was asked about the way he chooses the current and the electrode size. The answer was; "it depends on what you are used to". Whilst the welding speed or deposition rate deeply depends on these two parameters (19). The second case is when the fabricators' wages depend on piece work. The planned times are adjusted either because of the fabricator demand or based on the occasional study of the work by the planning section. The same argument, just explained, is also valid here except that the planned time may not be changed if the fabricator did not complain.

A survey on welding work in companies, by Doherty (6 Paper 19) has shown that the operation factor may vary between 20% to 77% from one company to another. This is a very clear reason for the human effect on the time changes and uncertainties in a fabrication time.
Therefore the equation should be adapted to suit a particular fabrication company.

6.10.16. Some Difficulties and a Simple Aid

In section 6.9.3.1. the practical weight distribution between the pieces of a component have been discussed. The effect of this type of weight distribution is to reduce the effect of the weight parameter in the time equation comparative to the even distribution of the pieces weights. Among the variables in the time equation, component weight is the most difficult to be determined, especially when the component is complex. But at the same time the weight estimation is simplified. Accepting the Pareto model for the weight distribution of a component, it can be used as a simple aid for the purpose. For most of components it is not necessary to estimate all of the pieces weights. One must first estimate the weight of the major important pieces in a component. It will then be increased by an appropriate percentage based on the current discussion (see also section 6.9.3.1.).

The "Pareto distribution" approach can help a designer in some other ways. For instance, by initial study of a component drawing, bearing in mind the detail of the time equation and the variables involved, one can judge on the major economical features of a component. Also he would be able to recognise the most concentrated work areas in a component. Another application of the approach is in the quick choice of welding factor and weld size (section 6.10.12). The approach can be developed to a quick and fairly accurate estimation of time or cost of a whole device, consisting of several fabricated components, and this
is what a designer with some experience requires to achieve.

6.10.17. A Nomograph for the Time Equation

The time equation can be represented by a nomograph (67). This will make the estimation quicker, though not with the same accuracy as the result that one can get by using the equations, because it is not possible to read the accurate values from a nomograph.

Figure 6.44. shows a nomograph which can be used to estimate the operation time of a fabrication when the welding process is semi-automatic. The nomograph consists of 9 columns, each of them represents one of the terms in the time equation as follows:

<table>
<thead>
<tr>
<th>Column</th>
<th>Description</th>
<th>Equation Term</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>two scales N1, N2</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>welding factor &amp; used as a base</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>T3</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>T2</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>T1</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>piece complexity, and used as a base</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>log scale &amp; normal scale for the same value</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>component weight</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>weld size</td>
<td></td>
</tr>
</tbody>
</table>

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6.10.16.1. How the Nomograph works and How to Use It.

Reading the number of the pieces N on the left side scale of column 1 (N₁) and joining it to the weld size on column 9, will intersect column 7 which gives the value of \((N^{0.32} + 8 + 0.9 t_w^{1.5})\) on the right side scale. Then take this value and find it on the left side scale and join it to N in column N₂. The intersection with column 2 gives \((N^{0.32} + 8 + 0.9 t_w^{1.5})(N - 1.6)^{0.5}\). Mark this point. Now find the weld factor F_w on column 2 and join it to the component weight on column 8, intersect column 7 will give; \(W^{0.48} \times F_w\). Join this point to the point that has already been marked on column 2. The intersection with column 5 will give T_w'. The last stage is to join this point to F_cb on column 6 to intersect the columns 4 and 3. Read the values on columns 3, 4 and 5 and add them together to give the total operation time, i.e.;

\[
T_{op} = (T_w' + 0.5 F_{cb} T_w' + 1.4 F_{cb} x T_w^{0.7}) \times 0.23
\]

This nomograph has been prepared without considering any particular adapting factor. One can very easily include any particular adapting factor in the nomograph to suit his own particular condition. The only thing to be done is to multiply the values on the columns 3, 4 and 5 by the adapting factor and put the new values instead of the present values.

It must be noticed that the values for all of the columns increase upwards except for column 6 which increases downwards.

**Example:** The values of the parameters for a particular component are
Weight \( W \) = 100 kg, number of pieces \( N \) = 30, weld size \( t_w \) = 5
piece complexity factor \( F_{cb} \) = 1.1 and welding factor \( F_w \) = 1.2.

Figure 6.45 shows the procedure and the result. First we join \( N = 30 \)
on column 1, \( N_1 \) to \( t_w = 5 \) on column 9 which intersects column 7 and we
read value 12 on the right hand scale and shift it to the same value
on the left side scale. This point is then joined to \( N = 30 \) from
column 1 \( N_2 \) to intersect column 2 at point 'P1'. Now \( W = 100 \) on column 8
is joined to \( F_w = 1.2 \) on column 2 to intersect column 6 at point \( P_2 \).
Joining \( P_1 \) to \( P_2 \) will intersect column 5 and we join this point to
\( F_{cb} = 1.1 \) on column 7. The values on columns 3, 4 and 5 intersected by
this last line are read and will be added together to find the total
operation time of the component i.e.

\[ \text{Top} = 150 + 90 + 35 = 275 \text{ min.} \]

The result from the equation is:

\[
T_w' = W^{0.48} \times F_w \left( N^{0.32} + 8 + 0.09 \times t_w^{1.5} \right) \left( N - 1.6 \right)^{0.5}
\]

\[
= 100^{0.48} \times 1.2 \left( 30^{0.32} + 8 + 0.09 \times (5)^{1.5} \right) \left( 30 - 1.6 \right)^{0.5}
\]

\[ T_w' = 698.46 \]

\[ \text{Top} = 0.23 \left( T_w' \left( 1 + 0.5 F_{cb} \right) + 1.4 \times F_{cb} \times \left( T_w' \right)^{0.7} \right) \]

\[ \text{Top} = 0.23 \left( 698.46 \left( 1 + 0.5 \times 1.1 \right) + 1.4 \times 1.1 \times (698.46)^{0.7} \right) \]

\[ \text{Top} = 160.65 + 88.36 + 34.7 = 283.7 \text{ min.} \]
Figure 6.45: An example for the time estimation by nomograph.
Figure 6.45a: A nomograph for estimating fabrication time (Eq. 6.25 & 6.28). The welding process is MMA welding. Setting time and adapting factor are NOT included.
Suggestion:

It is easily possible to convert the time values on columns 3, 4 and 5 to the operation cost for a particular company and also to make a new scale on column 8 for material cost.

6.10.18 Regression Approach

Referring to section 4.2.5, regression techniques have been suggested by many experts as being a useful tool for cost estimation. It could be used to correlate the manufacturing cost of products with the parameter involved. Some of the reasons for the inapplicability of this technique for the purpose have already been pointed out. The other important and experienced reasons are given here.

First of all the data available has been collected from different companies with different time features. Therefore it was not possible to find a general relation for all of them at the beginning. The general differences between the planned times should have been recognised whilst the similarity of time patterns between all of them were being studied. Even when the variables have been properly chosen, applying this technique will give the coefficient values such that the result of the relationship will be like the one shown in figure 6.46. Such a result is no help for cost estimation even if a better one could be achieved by a complicated equation. The proper choice of main variables was another stage that could not be reached by this technique since the number of possible variables were at first so many. Component volume is one of the variables that the technique will accept and is an important parameter for one group without any known reason. It could happen that
Here is the solution:

\[
\begin{align*}
X_1 &= 0.644063384586 \\
X_2 &= 0.30304158937 \\
X_3 &= -0.33263104368 \\
X_4 &= -0.08913559346 \\
X_5 &= 2.7787403914
\end{align*}
\]

A = 18.458037629

Here is the absolute error:

\[
\begin{align*}
&-0.000000017 \\
&-0.000000008 \\
&-0.000000023 \\
&-0.000000002 \\
&-0.0000000014
\end{align*}
\]

\[T_{\text{top}} = A \times X \times N \times X_2 \times t \times X_3 \times F_{\text{cub}} \times X_4 \times F_w \times X_5\]

**FIGURE 6.46**: Estimated Time by regression against Planned Time for four groups together.
a non-important variable with a complicated arrangement could introduce a relation to the 'time' if an important variable is neglected.

The data gives rise to other difficulties. One is the welding process which is manual for one group and semi-automatic for another. The analytical approach has shown that this difference could not be neglected. The other difficulty is that in most of the groups no component with edge preparation is available, and it was impossible to separate edge preparation time from overall time. On the other hand if one decided to use the technique for every group separately not only the number of the samples in a group would be small but the results from different groups will also be different, figures 6.47 to 50. Nevertheless this technique has been used here and there in this work to study some of the general relations for specific purposes. The one explained in section 6.10.8. was used only for general consideration. It was useful because a relation between welding time and cutting time in general started from this consideration. But the danger of detail study could lead to a set of different relations for each individual group which should be avoided. Taking from, or adding to, the samples in a group, even one sample, could change the equation coefficients significantly. Dealing with all of the samples in a group equally is another trap for the data with uncertainties. The data available are with this particular feature considerably (see chapter 5). The results from regression approach (figures 6.47 to 50) as well as from the derived equation (section 6.10.15) and the other studies of the groups have shown that some of the planned time for some of the components are irrelevant, while the regression equation is influenced by them.
Here is the solution:

\[ X_1 = 0.41998972273 \]
\[ X_2 = 0.3109985732 \]
\[ X_3 = 0.812956374 \]
\[ A = 48.5959741256 \]

Here is the absolute error:

\[ -0.00000000001 \]
\[ -1.0000000000E-13 \]
\[ -2.0000000000E-13 \]

\[ T_{calc} = A \times N \times X_1 \times X_2 \times X_3 \]

**FIGURE 6.47:** Estimated Time by regression against Planned Time for Group 1 (A).
Here is the solution:

\[ X_1 = 0.465753923647 \]
\[ X_2 = 0.57778140263 \]
\[ X_3 = 0.2433307958 \]
\[ X_4 = 0.7694956751 \]
\[ X_5 = 1.26287641563 \]

\[ \text{here is the absolute error:} \]
\[ \text{error} = 0.00000000002 \]
\[ \text{error} = -0.00000000001 \]
\[ \text{error} = -0.00000000006 \]
\[ \text{error} = 0.00000000002 \]
\[ \text{error} = 0.00000000005 \]

\[ T_{\text{top}} = A \times W \times X_1 \times N \times X_2 \times t_w \times X_3 \times F_{cb} \times X_4 \times F_w \times X_5 \]

FIGURE 6.48: Estimated Time by regression against Planned Time for Group 2 (B).
Noeqs = 5  Number of components = 18  Group 3 (C)

Here is the solution:

\[ X_1 = 0.547120066924 \]
\[ X_2 = 0.40549169087 \]
\[ X_3 = -1.46286488699 \]
\[ X_4 = 0.75479938802 \]
\[ X_5 = 1.13411910879 \]
\[ A = 16.7749265666 \]

Here is the absolute error:

\[ 0.0000000005 \]
\[ -0.0000000003 \]
\[ 3.1700000000E-11 \]
\[ -0.0000000005 \]
\[ -0.00000000003 \]

T_{top} = A \times H \times X_1 \times N \times X_2 \times \text{tw} \times X_3 \times Fcb \times X_4 \times Fw \times X_5

FIGURE 6.49: Estimated Time by regression against Planned Time for Group 3 (C).
Here is the solution:

\[
\begin{align*}
X_1 &= 0.27693936116 \\
X_2 &= 0.0039307706 \\
X_3 &= -0.03675020982 \\
X_4 &= 0.44902595585 \\
X_5 &= 2.2127095435
\end{align*}
\]

\[A = 28.329967704\]

Here is the absolute error:

\[
\begin{align*}
&-0.0000000024 \\
&-0.0000000013 \\
&-0.00000000135 \\
&1.75000000000E-11 \\
&-0.0000000018
\end{align*}
\]

\[T_{top} = A x X_1 x N x X_2 x tw x X_3 x Fcb x X_4 x Fw x X_5\]

**FIGURE 6.50**: Estimated Time by regression against Planned Time for Group 4 (D).
Although the analytical approach using standard times of detail processes has not led directly to a final result (sections 6.8. and 6.9), it has been used as a guide line to construct the core of the equation derived in section 6.10. The principles established in the analytical approach have been used to control reasonable changes. Whereas, following a regression approach could not have this advantage unless the structure of the equations had already been constructed. Even when one has achieved a usable relation by this approach, one may not be able to interpret it correctly. Since anyone without having any knowledge about a set of data can get a relation by using this mathematical approach, the actual relation between the variables may never be achieved. No wonder if this approach is being impressively recommended by, and to, manufacturing cost estimators. Finally, a short study of graphical results from this approach based on a multiple log relation of the same variables used in the original equations, i.e. W, N, t_w, F_{cb} and F_w (figures 6.47 to 50).

The coefficients are found to be different for different groups. Especially for group 1 (figure 6.47) with five samples, F_{cb} and F_w were not accepted since they were constant for all of the components in the group.

Nevertheless the step wise regression technique has been used to find the best combination of the five variables (W, N, t_w, F_{cb} and F_w) in a multiple variables equation either logarithmic or linear and the best
results are shown in figures 6.47 to 6.50.

One useful result which has already been found (section 6.10.12) is the side effect of piece complexities on welding time. A comparison between figures 6.51 to 53 and figures 6.54 to 56 shows how the relations have been modified by this effect. But in detail the coefficient differences could not be interpreted clearly. The major fact is that even if it was possible to use this technique with its most capability and get an equation similar to equations 6.25, 27 and 28 from so many different possible variables, two dark points still remained. An interpretation was required firstly and the equations were totally data dependent.
Here is the solution:

\[ X_1 = 0.475653278336 \]
\[ X_2 = 0.66732515988 \]
\[ X_3 = 0.43248994734 \]
\[ X_4 = 0.70985615853 \]
\[ X_5 = 1.38862931903 \]

\[ R = 0.896168368413 \]

Here is the absolute error:

\[ -0.000000003 \]
\[ 0 \]
\[ -0.000000002 \]
\[ -0.000000004 \]
\[ 0 \]

\[ Tw = A \times W \times X_1 \times N \times X_2 \times tw \times X_3 \times Fcb \times X_4 \times Fu \times X_5 \]

**FIGURE 6.51**: Joining Time by regression against Planned Joining time for Group 2 (B). Five variables are involved including piece complexity factor Fcb.
Here is the solution:
X1 = .552794601182
X2 = .494392171249
X3 = .059960381879
X4 = .470042503511
X5 = 1.45688436193
A = 6.47338830472

Here is the absolute error:
-0.000000000005
-0.000000000004
-0.000000000035
-0.000000000004
-0.000000000005

Tw = A x W x X1 x X2 x X3 x Fcb x X4 x Fw x X5

FIGURE 6.52: Joining Time by regression against Planned Joining time for Group 3 (C). Five variables are involved including piece complexity factor Fcb.
Here is the solution:

\[
\begin{align*}
X_1 &= 0.27171111746 \\
X_2 &= 0.791968306 \\
X_3 &= 0.0141501818 \\
X_4 &= -0.17193294147 \\
X_5 &= 3.068459353 \\
A &= 18.8864079069
\end{align*}
\]

Here is the absolute error:

\[
\begin{align*}
\text{Error} &= -0.0000000018 \\
\text{Error} &= -0.00000000098 \\
\text{Error} &= -0.0000000001 \\
\text{Error} &= 0.00000000015 \\
\text{Error} &= -0.00000000014
\end{align*}
\]

Tw = A x W x X1 x N x X2 x Tw x X3 x Fcb ^ x4 x Fw ^ x5

**FIGURE 6.53**: Joining Time by regression against Planned Joining time for Group 4 (D). Five variables are involved including piece complexity factor Fcb.
Number of components= 19

Here is the solution:
X1 = .563035971578
X2 = .48215037993
X3 = .127351810597
X4 = 1.78401445909
A = 2.21154807074

Here is the absolute error:
- .00000000001
0
- .00000000006
- .00000000009

Tw = A x N x X1 x N x X2 x tw x X3 x Fw x X4

FIGURE 6.54: Joining Time by regression against Planned Joining time for Group 2 (B). Four variables are involved, piece complexity factor Fcb is NOT included.
Here is the solution:

\[ X_1 = 0.54894967157 \]
\[ X_2 = 0.471384218621 \]
\[ X_3 = -0.03870235515 \]
\[ X_4 = 1.50605153608 \]
\[ A = 8.8823406092 \]

Here is the absolute error:

\[ 0.000000000002 \]
\[ 0.000000000018 \]
\[ 0.000000000001 \]

\[ T_w = A \times W \times X_1 \times N \times X_2 \times t_w \times X_3 \times F_w \times X_4 \]

**Figure 6.55:** Joining Time by regression against Planned Joining time for Group 3 (C). Four variables are involved, piece complexity factor Fcb is NOT included.
Here is the solution:
\[
\begin{align*}
X_1 &= 0.26960307462 \\
X_2 &= 0.8090970951 \\
X_3 &= 0.036455193845 \\
X_4 &= 2.973137056 \\
A &= 17.3468902583
\end{align*}
\]

Here is the absolute error:
\[
\begin{align*}
0.000000002 \\
0.000000009 \\
0.000000005 \\
0.000000002
\end{align*}
\]

\[
T_w = A \times W \times X_1 \times N \times X_2 \times tw \times X_3 \times F_w \times X_4
\]

**FIGURE 6.56**: Joining time by regression against Planned Joining time for Group 4 (D). Four variables are involved, piece complexity factor \( F_{cb} \) is NOT included.
6.11. Setting Time

6.11.1. Introduction

While joining time has been found to be the key process in a fabrication operation time, setting time is mainly related to piece preparation time. It is the variety of the processes involved in a fabrication that controls a component setting time and for a particular batch quantity it is the non repetitive part of any processing time (section 6.5.)

For a particular component, the significance of setting time in the total manufacturing time depends on several parameters.

6.11.2. Parameters

The parameters involved in a component setting time ($T_{set}$) are:

i) Batch quantity $Q$ (see sections 2.4.2 and 3.2.2)

ii) Number of items '$I$'. This is the piece variety in a component.

iii) Varieties in extra processes '$I_{cb}$'.

iv) Process or machine characteristics. The non repetitive part of the time for every single process is different (section 2.6.)

v) Number of pieces '$N$'.

vi) Sub-assemblies.

vii) Type of component. Simple or complex, light or heavy.
6.11.3. **Discussion**

The setting time for a component is estimated by the sum of setting times of the processes involved in the fabrication divided by the batch quantity 'Q'.

\[ T_{\text{set}} = \frac{\sum T_{\text{set}}}{Q} \]  \hspace{1cm} (6.31)

Every single piece in a component is assumed to be involved with one process at least. Then every item should require at least one setting time. Therefore if a component is made of I items which being cut with the same machine will have a total setting time for cutting process of;

\[ T_{\text{set}} \text{ (cuttings)} = \frac{I \times T_{\text{set}} \text{ (machine)}}{Q} \]  \hspace{1cm} (a)

But different pieces may be cut by different machines which depend on the material forms, thicknesses and the piece shapes (see section 2.6.). Typical setting times may vary from 5 to 17 minutes for different cutting machines. Therefore if the variety in the cutting machine for a component is i, equation (a) may be changed to:

\[ T_{\text{set}} \text{ (cuttings)} = \frac{\sum (I_i \times T_{\text{set}}^i)}{Q} \]  \hspace{1cm} (b)
where $\sum I_i = I$ and $T_{Set}$ represents the different setting times.

Component pieces may require some extra preparation processes, i.e. edge preparation, bending, extra hand burn, large inside cuts and so on. The variety in extra processes, $I_{cb}$, require different settings. If the variety in the machines doing extra processes is $j$ then equation (b) will be:

$$T_{set \text{ (piece prep.)}} = \frac{\sum (I_i \times T_{set \text{ i}}) + \sum (I_{cbj} \times T_{setj})}{Q}$$

where $\sum I_{cbj} = I_{cb}$.

6.11.4. The Effect of $N$ (number of pieces)

Every particular piece in a component with a specified batch quantity is produced as for one component multiplied by the batch quantity. Then one may consider the actual product quantity for that piece to be as the multiplication of these two values. Therefore when the ratio of $\frac{N}{I}$ for a particular component increases, it is as if the batch quantity has been increased indirectly. This feature will provide the same advantage in a cost reduction as the increase of a batch quantity. Consequently similarity in the pieces of a component could reduce the labour cost significantly. Similarity in between stiffeners is very easily achieved in a component design.

6.11.5. Assembly and Welding

Setting time in an assembly and welding process is not always quite
clear since it consists of understanding the drawings, getting the jigs and electrode required and setting the power equipment. In practice this part of the time, compared to the operation time is relatively very short. Sometimes companies do not consider any separate time for this part. But based on some of the data available a 10 minutes time has been accepted for every sub assembly for light and simple components or one may use 5 I/Q as an average setting time for this part of the process.

\[ T_{\text{set (ass.)}} = K \times I/Q \approx 5 I/Q \]  
(6.33)

6.11.6. Processes Setting Times

Although shop equipments are changed from time to time, so are the setting times, but a general guide line, based on the following information extracted from (3) is adapted for this purpose.

Piece preparation processes could be classified in three different groups for their setting times:

1) Machine cutting processes in general, such as machine oxygen cutting, guillotines, saws and nibbling. The setting time for this group varies from 10 to 17 minutes. Although the average is \( \approx 14 \) minutes, but it is possible to use even a minimum value 12 minutes, since in practice there is always some link between setting time of the items being cut from the same material and/or thickness.

2) Brake press bending, rolling, ring processing and so on. Setting time varies from 25 to 40 minutes. An average of 30 minutes is the most
common value for this group of process.

3) Manual processes like hand burn, hand manipulated nibbling, manual foot pectal bending or reciprocal cropper press etc. Setting time in this group varies from 5 to 8 minutes and the most common value in general could be taken as 6 minutes.

6.11.6. Practical Equation for Setting Time

Consequently an average setting time of 12 minutes has been assumed for all different pieces in cuttings. Manual processes are not being used so often. Then the first part of equation 6.32 is simplified;

\[ \sum (I_i \times T_{set_i})/Q = \frac{12I}{Q} \]  \hspace{1cm} (6.34)

6.11.7. Complexities Setting

Components could be classified in three different groups of setting time for their complexities;

i) Components made of plates less than 15 mm thick. The most important for this group is bending and after that large inside cuts. Thus for this group mainly one may use \( T_{set_j} = 30 \) minutes. Substituting equation 6.34 and this value in equation 6.32 and taking also equation 6.33 into account, the total setting time for this group will be

\[ T_{set} = \frac{12I}{Q} + \frac{30 \times I_{cb}}{Q} + \frac{5I}{Q} \]

or

\[ T_{set} = \frac{1}{Q} (17I + 30I_{cb}) \]  \hspace{1cm} (6.35)
ii) Components made of plates more than 15 mm thick. This group of components usually have edge preparation as the main piece complexities. Taking $T_{setj} = 12$ for this group, setting time will be;

$$T_{set} = \frac{1}{Q} \left( 17I + 12I_{cb} \right) \quad (6.36)$$

iii) Components made of sections usually have complexities being cut either by hand burn or by reciprocal cutting presses. Taking $T_{setj} = 6$ will change the setting time equation to:

$$T_{set} = \frac{1}{Q} \left( 17I + 6I_{cb} \right) \quad (6.37)$$

Note – As was mentioned earlier, the numerical factors in equations 6.35 to 37 have no general application before they have been checked for a particular shop. The general equation is produced here which is applicable in any particular shop based on its own standard setting times;

$$T_{set \ (total)} = \frac{1}{Q} \left[ I \ (K + T_{set}) + I_{cb} \times T_{setcb} \right] \quad (6.38)$$

where $T_{set}$ and $T_{setcb}$ and $K$ are to be specified for any particular shop.

6.11.6. When to Estimate Setting Time

There are some components where the setting times in comparison with the operation times is negligible. This depends on the component variables in the setting time equation (equation 6.38) and operation time equations. The first important parameter in the equation is $Q$ which is inversely
proportional to the setting time. Whereas number of items I is directly proportional to the setting time. Therefore when for a component with unsignificant piece complexities, \( Q > 10 \) and \( W > 100 \text{kg} \) has a ratio of \( \frac{I}{N} < 0.5 \). The setting time could be accepted to have a negligible effect on the total manufacturing time. Because for such a case the setting time will be almost \( 1.7 \) I and for any value of I since \( N > 2I \), the setting time is certainly less than \( 5\% \) of operation time. For instance, for component with say \( W = 110, N = 5, t_w = 3 \), \( Q = 12, I = 2, F_w = 1 \) and \( F_{cb} = 1 \), the operation time is \( T_{op} = 73.7 \) and setting time is \( T_{set} = 2.8 \) or \( \frac{T_{set}}{T_{op}} \times 100 = 3.8\% \), though the adapting factor is considered with minimum value i.e. \( F_a = 1 \). In contrast as the pieces become smaller and the component weight becomes lighter, the operation time will be relatively short so that for \( Q' < 5 \) setting time is much more significant than operation time. For these types of components, two important points are to be noticed by designers. First, since bending process has a relatively high setting time (30 mins.) it is recommended not to use bends in the design of this type. Secondly, the number of items must be kept as low as possible.

The component weight has a side effect on assembly setting time by the effect of jig settings. But heavy components, particularly with big weld sizes, have relatively low setting times even in a small batch quantity.

6.12. An Actual Component

6.12.1. Accuracy and Complexity of the Equations

Every particular component has some special manufacturing features which
the introduction of them all into a general equation is not feasible. Therefore some inaccuracies for the results from the present equations are to be expected, so that for more than 80% of components the actual time will be within a margin of ± 15% from the estimated values. In other words, if one plots the actual times against estimated times for a number of different components a band of points will be created that the width of the band is equal to the margin of inaccuracies i.e. ± 15%.

One may find, on the other hand, that the equation is so complicated that a designer may not be willing to use it. Unfortunately this could not be avoided, since, firstly, the variables chosen are so effective in the result that none of them could be eliminated without losing the present accuracy for such a wide range of components. For instance, if one chose to use an equation for estimating operation time as follows:

\[ T_{top} = K W^{0.5} \times N^{0.5} \times F_w \times F_{cb} \]  

(6.39)

The result will only be accurate to ± 30% for many components; the application will also be reduced to a very small range of components. The constant values require to be adjusted for different ranges.

Secondly, during the development of the equation, the simplicity has always been regarded as one of the main criteria in the specification. Moreover, when a designer accepts the time he spends to analyse and calculate the stresses in a component, he should also appreciate spending a similar period of time to estimate the component cost. The
validity of this argument could be extended to the comparison of the equations' complexity.

6.12.2. Batch Quantity as a Shop Feature

The cost effects of the batch quantity for a component could be considered as a shop feature, which may change setting times as well as operation times. The cost of the component accuracy reduces with the increase of the batch quantity. Special jigs with more accuracy would become more feasible when a batch quantity permits it. When Q is low, say Q < 5, most of the assemblies are carried out with the aid of general purpose jigs and clamps. This type of assembly is more time consuming than using special jigs. It makes the positioning to be an important component feature which must be considered in the weld factor.

Scrap reduction in a shop (Nest and Gain) will decrease the factor of overhead. When 'Q' is high enough, using multi-torch cutting or stack cuttings could reduce a setting time as well as operation time.

Note - Multi-torch cutting does not reduce an operation time very much since the cutting speed, in this process, is comparatively reduced (11).

6.12.3. Special Accuracies

General accuracies in a shop depend on the equipment available and the common products. It is taken as a part of the adapting factor $F_a$ in an operation time equation. But a special accuracy in a component is a feature that requires special care which is different from the normal approach in a shop. It could be either because of the component
load, prefabricated machined parts and so on. However, they are difficult to be quantified here unless by actual study of any particular case based on experience and a shop detail.

When a component, or a joint in particular, is not under a significant load, the control of the welding process as well as the time could be down to a minimum. Casual intermittent welds is a component characteristic that will lower a welding factor.

6.13. Material Cost

Applying the standard method of material costing (39), the actual material used for a fabricated component consists of two parts; the material which has been specified in the design and material variances. The material variances develop from:

1) Schedule of quantity
2) Scrap losses
3) Learning curve effect on scrap loss.

6.13.1. Batch Quantity and 'Nest and Gain'

One of the most important, and most frequently overlooked, factors is the 'nest and gain' factor \( F_{ng} \) which results from changes in quantity or schedule. This variance is generated during cutting pieces from either plates or flats. This is a material excess variance or 'gain' which is purely a result of schedule and quantity. Failure to recognise it will create an underestimation of the material cost. Figure 6.57 shows the effect of nesting in a plate (9). In this instance, by combining the pieces into a single layout, a significant material savings
Figure 6.57: Typical example for nesting different pieces in one plate. (9)

is realised. But this is possible if the requirement is balanced with quantity. Such an arrangement can reduce the plate waste from 40% down to 10%. Cutting pieces randomly in a plate is common in a one-off product which can result in a material waste of 30% to 40% (section 5.2.). If component is made of sections this concept is usually insignificant.

6.13.2. Scrap Losses

Scrap losses are caused by random error, machine or material failure, operator’s error and design errors. In all cases they tend to vary with product quantity, complexity, precision and production experience.
The formula for predicting scrap loss on a realistic base (39) is:

\[ S = W \times \frac{1}{\sqrt[4]{Q}} \]  

(39)

where \( Q \) = Batch quantity  
\( W \) = Component weight  
\( S \) = extra material required for predicted defects

It was already mentioned that the ratio of the number of pieces to the number of items i.e. \( \frac{N}{I} \) for a particular component affects the batch quantity \( Q \) (section 6.11.4), so that the actual \( Q \) in piece preparation stage can be considered to be

\[ Q' = Q \times \frac{N}{I} \]

Therefore the scrap loss is estimated as follows:

\[ S = \frac{1}{\sqrt[4]{Q'}} \times W = \frac{W}{\left(\frac{Q \times N}{I}\right)^{0.5}} \]  

(6.40)

6.13.3. The Effect of Learning Curve on Scrap Loss

In most operations experience causes a reduction in both labour cost and scrap loss. The "learning curve technique is often used to project this experience effect". The learning curve is a graphic presentation of the improved performance growing of increasing quantities and increasing skills and experience" (31). In an 80% learning curve situation, each time the quantity of units produced is doubled, the cumulative average pieces scrapped will approach 80% of the average scrap in the initial quantity. Thus if for a batch of 100 components, 10
components were scrapped, for a batch of 200 components, 8 components will be scrapped/100 components produced.

It can be noticed that the learning effect on scrap reduction in low batch quantities is not significant. Moreover in piece preparation the machine and/or operation will be set for the whole batch at once and templates are used for the purposes. So one can say that learning to reduce scrap takes place as the operation is set for full production runs.

Consequently, the amount of material to be charged to the cost equation should include the design standard material $W$, as well as the 'nest and gain factor' $F_{ng}$ and the scrap loss per component, i.e.

$$M = W \left(1 + F_{ng} + \sqrt{\frac{1}{QN}} \right)$$  \hspace{1cm} (6.41)

and the total material cost is

$$C_M = M \times \text{(standard cost/kg of material)}$$  \hspace{1cm} (6.42)


Consumable cost is considered either in the overhead and proportional to the labour cost (14,53) or as a part of material cost (6, Paper 1). When included in overhead, it is taken as 20% to 30% of labour cost, and when in material cost, the weight of the weld material is about 1.5 to 4 per cent of component weight and the unit price of weld material is about 6 times the unit price of steel. Since the weld material in a
particular component is proportional to the welding time, therefore it can be assumed that the weld material changes for different component is proportional to the welding factor i.e. $F_w$ in the welding time equation, so that when welding factor, $F_w$, is minimum i.e. 0.5, the weld material is 1.5% of the component weight and when welding factor is maximum, i.e. 2, the weld material is 4% of the component weight. Therefore the weld weight can be estimated as follows:

$$W_E = W(5F_w + 2)/300 \quad (6.43)$$

The cost of the weld material for a particular component is

$$C_E = W_E \times \text{(standard cost/unit weight of electrode)}$$
7.0. Designers Guide

7.1. Introduction

There were many important economical points notified through this work that a designer should regard as principles to establish the design of fabricated components. Costing is one part but to design within an economic envelope is the other main aim of this work. They have to be practised beside each other.

There is much advice about how to design a fabrication with economy, in references especially in (3). The following points are those which the author has found during his experience to be the most important and practical ones.

7.2. Designers' Information Required

7.2.1. Design Preparation

Before starting a design activity, a designer should have proper knowledge about fabrication work. Lack of following information would leave him with a lot of uncertainties and mistakes. The main advice here is not to start a fabrication design before this preparation.

i) Materials available: A list of materials available, costs, forms, sizes, priorities in relation to general products in the shop and the applications should be prepared. This list should be checked by the shop stock.

ii) Shop facilities: The equipment available in the shop, applications and capacities, feedings, handling equipment, general purpose jigs and manipulators and the others should be known. All the processes involved
in a fabrication should be watched and studied carefully. This is to understand the actual difficulties involved in the work as well as the time consumer processes in the shop. General accuracies and batch quantity of the products in the shop, inspections, assembly difficulties and scrap control should be known, and a list similar to the one in table 6.2. is to be prepared. A list of punch dies and other special tools available is useful. What is the information that a production engineer expects to find in a manufacturing drawing and how does he use it?

iii) Load: Load understanding in relation to a fabrication design is a knowledge that one must be capable of. Load types and load applications affect the choice of forms, joints and their locations. These differences affect the component cost, (4, Chap. 5). The choice of sections and forms also depend on the load type and the applications. Designs for non significant load, strength or rigidity are to be different in detail as well as in costs. A design which is economical for one purpose may be considered expensive for another purpose.

iv) Jig Design: A knowledge of jig design in metal fabrication is also a vital need for a designer. It must be related to a batch quantity and the shop requirements.

7.3. How to Start
To start the design of a particular component a list of special requirements is to be prepared i.e. component specification. This is to be done at least for the main components in a device. Decision on whether to choose fabrication or other processes usually starts at this stage.
7.3.1. Right Material in Right Place
Proper usage of material is one major step in a good design. This is possible if, firstly, the information mentioned earlier is accessible and, secondly, if the load specification of a component is used based on load line approach properly (26). Over design increases the material and labour cost. Such a design should not be compared with a casting. Cracks and internal defects are more likely to happen in joints with thick materials and weld sizes. Simplicity which is another face of low cost production could be achieved by following the approach above mentioned. Wherever possible, use sections and forms to reduce the material and joints.

7.3.2. Welds and Joints
A weld size should be calculated based on the maximum possible weld length for a particular joint i.e. do not assume the weld size first. Weld size variation in a component is to be avoided since it is difficult to control and inspect. One may specify weld size in a component based on stress analysis, but they should be modified finally to feasible sizes.

7.3.3. Other Points
Considering all of the fabricated components of a device simultaneously can reduce the components costs as well as the cost of the costing. Similar choice of materials and processes for these components will reduce scrap, general handlings and settings, since they will be manufactured at the same time with the same batch quantities.

Think about the subassemblies and jigs while designing a particular
component. Also those complexities and accuracies that require special processes should be avoided, e.g. manual processes are relatively high time consumers with less control. Difficulties in fit-up should be known (4, Sec. 5 & 6) and avoided.

Machining processes which will be followed after fabrication of a component should be considered while design is in progress. Sometimes a design with low fabrication cost may require lengthy machining processes. Simply it is the economy of a final product that should be controlled at the design stage.

Use bends when batch quantity 'Q' is sufficient to compensate the high setting times. Check the setting times for different processes available in the shop.

Reduce the number of items 'I' and material varieties in a component. This will reduce the process settings.

Determine the values for the parameters required in a cost estimation while designing a component. That will make costing faster.
7.4. How to Cost a Fabrication

This is the summary of the whole fabrication costing. The list of the variables used in the equations is shown at the end of this section.

Referring to equation (6.1.) in section 6.1., the manufacturing cost of a metal fabrication is:

\[ C_{\text{fab}} = \text{Material Cost} + \text{Electrode Cost} + \text{Labour Cost} \]

or

\[ C_{\text{fab}} = C_M + C_E + C_L \]

From equation (6.42) in section 6.13.3 the material cost is

\[ C_M = M \times (\text{material unit cost}) \]

where;

\[ M = W \left( 1 + F_{\text{ng}} + \sqrt{\frac{I}{Q}} \right) \]

Electrode cost is either considered based on labour cost, and is included in the manufacturing overhead or it can be estimated based on the component weight by using equation (6.43);

\[ C_E = W_E \times (\text{electrode cost unit}) \]

where;

\[ W_E = W \left( 5 F_w + 2 \right)/300 \]

Labour cost is: \[ C_L = T_{\text{fab}} \times F_{\text{OH}} \times (\text{labour cost per hour})/60 \]

where;
\[ T_{\text{fab}} = T_{\text{op}} + T_{\text{set}} \]

Setting time is estimated by equation (6.38) which is

\[ T_{\text{set}} = \frac{1}{Q} \left[ I (K + T_1) + I_{\text{cb}} \times T_2 \right] \]

where \((K + T_1)\) and \(T_2\) are constants for a particular shop. Typical values are \(K + T_1 = 17\) and if the component is made of plates < 15mm thick take \(T_2 = 30\), if it is \(\geq 15\)mm thick take \(T_2 = 12\) and if the component is made of sections take \(T_2 = 6\).

Setting time can be ignored in many cases discussed in section 6.8.11.

Operation time can be estimated by any of the following four different approaches. These approaches are represented here, in the order based on the range of application, accuracy and the speed of estimating operation;

Method 1:

If the designer is working on a range of components with the same range of weld sizes (or plate thicknesses) and same complexities, he can estimate the operation time by;

\[ T_{\text{op}} = F_1 \times (W \times N)^C \quad (a) \]

where \(C\) and \(F_1\) are constants which can be determined based on the planned time available for similar products in the shop. Preparing a graph in log-log mode of \(T_{\text{op}}\) or \(C_L\) against \(W \times N\) for the planned times available will be useful for the purpose. This will indicate the range of components which their operation times or labour costs can be estimated by the equation specified. It is also possible to use the graph directly for
the time estimation (section 6.10.7). Obviously the more similarity between the components the more accurate will be the time estimated. The value for $C$ can be expected to be somewhere between 0.5 and 0.7. The value of factor $F_1$ not only depends on the range of the components and their particular features, but also it is a company dependent i.e. it depends on the operation factor, shop efficiency, as well as shop facilities and the batch quantity.

**Method 2:**

For a wider range of components' complexity, one can prepare a graph in log-log mode for the available planned time for the components in the same range against the values estimated from equation:

$$T_{op} = F_2 \times F_w \times F_{cb} \times (W \times N)^{C_1}$$

where an initial value for $C_1 = 0.5$ can be applied at the beginning and adjusted afterwards if required. $F_2$ is a factor similar to $F_1$ in equation (a) with the same dependencies.

**Method 3:**

The most general and accurate approach for estimating operation time is to use equations (6.25, 27 and 28) in section 6.10.10, i.e.

$$T_{op} = (T_w' \times (1 + 0.5 F_{cb}) + 1.4 F_{cb} T_w'^{0.7}) \times 0.23 \times F_a$$

where $F_a$ is an adapting factor depending on the operation factor and/or the efficiency of the shop. A typical value for it is $F_a = 3$.

$T_w'$ depends on the welding process and is estimated as follows:
For semi-automatic CO₂ welding use:

\[ T'_w = W^{0.48} (N^{0.32} + 8 + 0.09 t_w^{1.5}) (N - 1.6)^{0.5} x F_w \]

For manual welding (MMA) use:

\[ T'_w = W^{0.48} (N^{0.32} + 10 + 0.2 t_w^{1.6}) (N - 1.6)^{0.4} x F_w \]

Method 4:
A quicker way than the last approach is to use a nomograph like the one in section 6.10.17 (figure 6.44) which has been prepared for estimating the operation time when the welding process is semi-automatic CO₂ welding.

The list of the variables used in the equations in this section is as follows:

- \( C_E \) = Electrode cost
- \( C_{fab} \) = Fabrication manufacturing cost
- \( C_L \) = Labour cost
- \( C_M \) = Material cost
- \( C \) = Constant factor for a range of similar fabrications with similar complexities
- \( C_1 \) = Constant factor for a range of fabrications with similar range of material and weld size
- \( F_1 \) = A constant factor for similar components in a company
- \( F_2 \) = A constant factor for similar components as explained
- \( F_a \) = Adapting factor for operation time which is constant in a shop
- \( F_{cb} \) = Piece complexity factor = \( 1 + \frac{N_{cb}}{N} \)
\[ F_{ng} = \text{Nest and gain factor which is constant for a shop. It ranges between .1 to .4 (10\% to 40\%) depending on the batch quantity and schedule.} \]

\[ F_{OH} = \text{Overhead factor in the shop} \]

\[ F_{w} = \text{Welding factor to be determined by using Table (6.4)} \]

\[ I = \text{Number of items or piece variety in the component} \]

\[ I_{cb} = \text{Variety in the piece complexities in the component} \]

\[ K = \text{Constant of setting time of the assembly depending on the shop and the batch quantity, a typical value is } K = 5 \]

\[ M = \text{The amount of material to be charged for material cost of the component per kg} \]

\[ N = \text{Number of pieces in the component} \]

\[ N_{cb} = \text{Number of piece complexities, i.e. bends, large inside cuts, manual cuts, edge preparations and the like} \]

\[ Q = \text{Batch quantity of the component} \]

\[ T_1 = \text{Setting time (minute) for cutting process of one piece, which is constant in a shop. A typical value is } T_1 = 12 \text{ minutes} \]

\[ T_2 = \text{setting time (minute) for extra process in piece preparation, which is constant in a shop} \]

\[ T_{fab} = \text{Total fabrication time (minute)} \]

\[ T_{op} = \text{Total operation time of a fabrication (minute)} \]

\[ T_{set} = \text{Total setting time of a fabrication (minute)} \]

\[ t_w = \text{weld size (millimetre) or leg length of weld (average)} = \sqrt{\frac{2t_w}{N-1}} \]

\[ W = \text{Component weight (kg)} \]

\[ W_E = \text{Electrode weight (kg) required in the welding} \]
7.5. An Alternative Version of Fabrication Costing

\[ C_E = \text{Electrode cost} = W_E \times \text{(electrode cost unit)} \]

\[ C_{\text{fab}} = \text{Manufacturing cost of the fabrication} = C_M + C_E + C_L \]

\[ C_L = \text{Labour cost} = T_{\text{fab}} \times F_{\text{OH}} \times \left( \text{labour cost unit per hour} / 60 \right) \]

\[ C_M = \text{Material cost} = M \times \left( \text{material cost unit} \right) \]

\[ C = \text{Constant factor for a range of similar fabrications with similar complexities} \]

\[ C_1 = \text{Constant factor for a range of fabrications with similar range of material and weld size} \]

\[ F_1 = \text{Constant factor for a group of similar fabrications (see sec. 7.4 method 1)} \]

\[ F_2 = \text{Constant factor for a group of fabrications (see sec. 7.4 method 2)} \]

\[ F_a = \text{Adapting factor for operation time which is constant in a shop} \]

\[ F_{\text{cb}} = \text{Piece complexity factor} = 1 + \frac{N_{\text{cb}}}{N} \]

\[ F_{\text{ng}} = \text{Nest and gain factor, constant for a shop. It ranges between } .1 \text{ to } .4 \text{ depending on the batch quantity and schedule} \]

\[ F_{\text{OH}} = \text{Overhead factor, constant in a fabrication shop} \]

\[ F_w = \text{Welding factor, to be determined by using Table 6.4.} \]

\[ I = \text{Number of items or piece variety in the component} \]

\[ I_{\text{cb}} = \text{Variety in the piece complexities in the component} \]

\[ K = \text{Constant of setting time of the assembly depending on the shop and the batch quantity. A typical value is } K = 5 \]

\[ M = \text{The amount of material (kg) to be charged for the material cost of the component.} \]

\[ M = W \left( 1 + F_{\text{ng}} + \sqrt{\frac{I}{QN}} \right) \]

\[ N = \text{Number of pieces in the component} \]

\[ N_{\text{cb}} = \text{Number of piece complexities i.e. bends, large inside cuts, manual cuts, edge preparations and the like} \]
\[ Q = \text{Batch quantity of the fabrication} \]
\[ T_1 = \text{Setting time (minute) for cutting process of one piece,} \]
\[ \text{constant in a shop. A typical value is } T_1 = 12 \text{ minutes} \]
\[ T_2 = \text{Setting time (minute) for an extra process in piece preparation,} \]
\[ \text{constant for a shop} \]
\[ T_{\text{fab}} = T_{\text{op}} + T_{\text{set}} = \text{Total fabrication time (minute)} \]
\[ T_{\text{op}} = (T'_{\text{w}}(1 + 0.5 F_{\text{cb}}) + 1.4 F_{\text{cb}} T'_{\text{w}}^{0.7}) \times 0.23 \times F_a = \text{total operation time (minute)} \]

For a range of similar fabrications with similar complexities it is;
\[ T_{\text{op}} = F_1 \times (W \times N)^C \]

For a range of fabrications with similar range of material and weld size it is;
\[ T_{\text{set}} = \frac{1}{Q} \left[ I(K + T_1) + I_{\text{cb}} \times T_2 \right] = \text{total setting time of the fabrication (minute)} \]
\[ t_{\text{w}} = \text{weld size (millimetre) or leg length of the weld (average)} = \left( \frac{\Sigma(t_{\text{w}}^2)}{N-1} \right)^{0.5} \]

\[ T'_{\text{w}} = \text{For semi-automatic CO}_2 \text{ welding it is} \]
\[ T'_{\text{w}} = W^{48} \left( N^{-32} + 8 + 0.09 t_{\text{w}}^{-1.5} \right) \left( N^{-1.6} \right)^{0.5} \times F_w \]

For manual welding (MMA) it is
\[ T'_{\text{w}} = W^{48} \left( N^{-32} + 10 + 0.2 t_{\text{w}}^{-1.6} \right) \left( N - 1.6 \right)^{0.4} \times F_w \]
\[ W = \text{Component weight (kg)} \]
\[ W_{\text{E}} = \text{Electrode weight (kg) required in the welding} \]
7.6. Conclusion

The present study has shown that costing of metal fabrication in low to medium batch quantity is not easy to carry out, especially for a designer, since it is a multi process product which is being produced both manually and semi-automatically. The effect of the human factor on the time required is significant, so that it is almost impossible to generalise the costing for different companies.

The main aim of this work is to introduce the most important design parameters affecting the economy of a fabrication and to represent these parameters in a costing system to be used by designers. The difficulties in the achievement of an accurate result have been pointed out and the different options in the approach have been suggested. Classifying similar components in a group can make the costing significantly easier, since it will reduce the number of contributing parameters as well as the difficulties in the choice of proper welding factor. The equations for the time estimation have also been produced in the form of a nomograph which can save extensive computations. It is very easy to operate and once the parameters of the design are determined, using the nomograph will give the result very quickly. The time values on the nomograph can be converted to cost values for any particular company.

The system can be used in concept evaluation, and to modify a design from the economical point of view. It is also possible to apply the method for the evaluation of concepts which consist of several fabricated components.

It is suggested that the time and consequent cost of applying this
system would be small in comparison to the time and cost savings achieved.

The designers' need for an easy, simple and reliable tool (i.e. a cheap tool) to forecast the cost of a fabrication design on the one hand and the wide variety of fabrication parameters affecting the manufacturing cost plus lack of sufficient and reliable data from companies on the other has led the author to compromise between these contrasting requirements. The results achieved have not covered all of the fabrication areas and is not the end of the road but it is the road on its own. One can follow and develop it for other types of fabrications and relevant processes which have not been covered because of the time limit.
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APPENDIX (A)
## LIST OF RELEVANT BRITISH STANDARDS

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APPENDIX (B)
Research: Fabricating Cost at Design Stage
Questionnaire

(Colmn)

Firm name and address .................................................................
.................................................................................................

1- Number of labours ............

2- Number of labours in the fabricating section:

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3- Tasks of unskilled labours, and the ratio of wages (Skilled labour/Unskilled labour)?

4- Fabricating equipments for the operations mentioned above (type and number):

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</table>
5- Handling and Assembly equipment; jigs, fixtures & manipulators - multipurpose and specials?

6- Choice of processes and equipment for fabrication;
   Who?
   When?
   How?
   Parameters & factors? references? any problem?

7- Typical applications of equipments?

8- Is there any predominant fabricating processes?
   If yes, what are the typical applications and why?

9- Is there any "flowline" in the fabricating section?
   If yes, what?

10- Range of the metal thicknesses, plates and sections (steel, B.S. 4360)?

11- Range of the fabricated components; weights, sizes /or any other classification
    e.g. processes, accuracy, materials & sections etc.?

12- Choice of consumables, who? When? how?
    Parameters? References and data? Range of consumables? Wastes?

13- Choice of the joints positions; who? how? what?

14- The relation between the component weight and the material wastes?
    Remember; Wastes = Scrap + Defects

15- How do you solve the "nest & gain" problems?
    In a range of components, a range pieces, one component, or one piece?

16- What is the range of precisions?
    Does it affect the choice of equipment/or other decisions?

17- Choice of the number of the passes?
    How? Any reference?

18- How do you make decision on a new equipment for a new component?

19- What parts of the processes are specified in the drawings?
Cost Estimator

  Any cost sample, cost model, or unit cost?

- Do you use any computer programme for cost estimation of components?


- What is the overhead cost of fab. comps.? What are the details.

- Estimation of the metal costs (steel B.S. 4360)? Total weight? Sections? How much is the wastes?

- Consumables costs? How? Deposition Rates?
  Wastes, Efficiencies, Electrode stud in manual welding?


- How do you estimate and what is: Operation factor or D.C., Learning factor, and Factor of the No. in a batch? Are they the same for all jobs?
1- Do you ever estimate the cost of components during the detail design stage? If yes, how?

2- How do you choose materials, sections and processes for fabricated components? Parameters, criteria and references? Any detail?

3- Choice of joint type; square, V, J, single, double, sealed, backed, etc.? How? Parameters? References?

4- Do you specify the detail of "heat treatment", "inspection and sampling" in the drawings? How?

5- Your idea about a quick cost estimation at the detail design stage? Any commence?
Figure C.1

 Thickness: $\frac{1}{4}''$, $1''$, $1.5''$, $2''$, $2.5''$, $3''$

 Length of cut per piece (inch)

 Operation Time (min.) with out template

 Pieces Lighter than 50 lb.
 Pieces 50 to 200 lb.
Figure C.2: Flame cutting—Hand torch
Cutting time against plate thickness, when cutting length is constant.
Flame Cutting—Hand Torch

Setting time 11 min.
## Standard Work-Factor Arm Movement Ref. 66

### Arm

<table>
<thead>
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<th>Distance</th>
<th>Basic</th>
<th>Work_F1</th>
<th>Work_F2</th>
<th>Work_F3</th>
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<td>109</td>
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Weight in lb
- 2 7 13 20

---

### Diagram of Work-Factors

- **Distance in Inches:**
  - 10
  - 20
  - 30
  - 40
  - 50

- **Weight without Work:**
  - 7 lb
  - 13 lb
  - 20 lb

- **Weight with Work:**
  - 2 lb
  - 7 lb
  - 13 lb
  - 20 lb

---

Ref. 66
Work-Factor Motion Time Analysis:
Time (in .0001 minute) x Weight (in lb) - Weight (in lb) + .4
Arm movement

Time, in 1000 minutes

Distance, in Inches

Height > 20 lb
Height = 20 lb
Height = 13 lb
Height = 7 lb
Height = 2 lb
Standard Work-Factor Time - Leg movement. Ref. 66

--- Leg ---

<table>
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<tr>
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<th>Work_F2</th>
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Weight in lb

--- Graph ---
Leg movement

- Weight >42 lb
- Weight =42 lb
- Weight =8 lb
### Standard Work-Factor Time

**Trunk Movement**

Ref. 66

---

**Distance** | **Basic** | **Work_F1** | **Work_F2** | **Work_F3** | **Work_F4**
---|---|---|---|---|---
4 | 38 | 55 | 70 | 84 | 96
5 | 43 | 62 | 79 | 95 | 109
10 | 61 | 88 | 113 | 135 | 155
15 | 73 | 103 | 133 | 163 | 188
20 | 84 | 116 | 148 | 179 | 209

**Weight in lb**

11 | 58

---

| Weight >58 lb | | | | |
| Weight =58 lb | | | | |
| Weight <11 lb | | | | |
Trunk movement

- Weight >50 lb
- Weight =50 lb
- Weight =11 lb

DISTANCE in Inches
APPENDIX (E)
All positions
Electrode Type = Cellulose
Efficiency = 93%
(ref. 19 table 1)

<table>
<thead>
<tr>
<th>Weld size</th>
<th>Electrode size</th>
<th>Position Symbol</th>
<th>Time</th>
<th>Deslag &amp; cleaning</th>
<th>Arc time per m</th>
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Position symbol:
F = Flat
H = Horizontal

All positions
Electrode Type = Rutile
Efficiency = 93.5%
(ref. 19 table 2)

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All time values expressed in Basic Minutes, WITHOUT allowances.
### All positions

**Electrode type = Rutile**  
**Efficiency = 130-135%**  
(ref. 19 table 3)

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**F = Flat**  
**H = Horizontal**

### Flat and Horizontal positions

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**Efficiency = 135-145%**  
(ref. 19 table 4)

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Allowances are NOT included in the time values
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**F = Flat**  
**H = Horizontal**

Allowances are **NOT** included in the time values.
MANUAL METAL ARC WELDING; FILLET WELD, WELDING TIME (REF. 19)

All positions
Electrode Type = Basic hydrogen controlled
Efficiency = 103% (ref.19 table 7)

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All positions
Electrode Type = Basic hydrogen controlled
Efficiency = 115% (table 9)

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F = Flat  H = Horizontal

Allowances are not included in the time values.
SEMI-AUTOMATIC CO2 METAL ARC WELDING, FILLET WELD, (Ref. 19)

All positions, Solid wire

Electrode diameter = .8mm
Efficiency = 96%
(ref. 19 table 111)

<table>
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Efficiency = 95%
(table 112)

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Efficiency = 95%
(table 113)

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F = Flat  H = Horizontal

Allowances are NOT included in the time values
Ref. 19 table 11.
SEMIAUTOMATIC CO2 METAL ARC WELDING, (Ref. 19)

All positions

Solid wire

Electrode diameter = 1.6 mm

Efficiency = 94%

(Ref. 19 table 114)

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Flat & Horizontal

Flux cored electrode

Electrode diameter = 2.4 mm

Efficiency = 79%

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Flat & Horizontal

Flux cored electrode

Electrode diameter = 3.2 mm

Efficiency = 76%

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Allowances are NOT included in the time values.

F = Flat    H = Horizontal
Semi-automatic CO2 Welding
Ref. 19 table 114

WELDING TIME in minutes

WELD SIZE in millimeters

100

10
Semi-automatic CO2 Welding
Ref. 19 table 118

WELD SIZE in millimeter

WELDING TIME in minutes
Semi-automatic CO₂ Welding
Ref. 19 table 116

WELDING TIME in minutes

WELD SIZE in millimeter
Weld Weight kg - Weld Size m
Ref. 3 table: 6-4-2

WELD WEIGHT in kg

WELD SIZE in millimeter