Small Volume Fabrication Cost Estimation Models for Embodiment Design

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Manufacturing cost estimation is an integral part of design for manufacturing. Cost estimation models are presented for fabricated mild steel welded assemblies, between a few hundred grams and five ton, made in small production volumes. Data collected in time studies at five South African companies was cast into a times and rates approach, using robust statistical techniques. The models are aimed at the early embodiment design phase, to help the designer to optimise the design for fabrication and to compare fabrication with alternative processes. The application of the models to evaluate the redesign of a fabricated assembly is demonstrated.

NOMENCLATURE

$A_{material}$	Sheet material area [mm^2]
A_{part}	Projected part area [mm^2]
A_{weld}	Cross sectional area of weld seam [mm^2]
B_{sheet}	Is the part a sheet [boolean]
c_a	Critical alignment with external feature [boolean]
F	Flexibility [boolean]
L_b	Bend length [mm]
L_{cut}	Length of cut [mm]
L_j	Length of welding joint [mm]
m_{hand}	1 for manual handling, 0 for mechanical handling
m_{part}	Part mass [kg]
n_{angles}	Number of different angles per part
n_b	Batch size
n_{holes}	Number of holes per part
$n_{nozzles}$	Number of nozzles on a flame cutting machine
n_{nstd_angles}	Number of non-standard angles per part
n_s	Number of parts per sheet
n_{std_angles}	Number of standard angles per part
n_w	Number of welding joints
S	Size [mm]
t	Time per part [s]
t_c	Critical sheet thickness parameter: 1 if sheet is thicker than 30mm, 0 otherwise.
t_{fd}	Alignment feature's principal dimension [mm]
t_w	Material thickness [mm]
θ	Symmetry angle [°]
θ_b	Bend angle [radians]

Introduction

The CAD Laboratory at Stellenbosch University developed manufacturing cost estimation models for mild steel welded assemblies in small production volumes in South Africa. Researchers gathered cost data in five different companies, as documented by Maree[1], Schuster[2], Schreve[3] and De Swardt[4], from which the models were developed. The cost estimation models are aimed specifically for use in the early phases of embodiment design, with the corresponding limits to information available and accuracy achievable. The design scenarios encountered in a small production volume environment often includes that the potential manufacturers of a part or assembly are only known after completing the detailed designs and submitting them for quotations to manufacturers. Information relying on the knowledge of a specific manufacturer could therefore not be used in the cost models.

The role of cost estimation and design for manufacturing in the design process is considered in the following section. The approach used in developing the cost models presented here, and the resulting models are then described. The use of the cost models in comparing alternative designs is finally demonstrated.

Manufacturing Cost Estimation in the Design Process

Design for manufacturing starts with the selection of the manufacturing processes most suitable for a part and then adapting the part's design to those processes. Selection and adaptation recurs in the design process, at increasing levels of refinement and detail. Cost estimation is an integral part of this process, even if only implicitly. In addition to the cost, other factors not addressed in this paper also play significant roles, e.g. material constraints imposed by functional requirements, time considerations, company policy (such as preference for in-house manufacture or outsourcing), etc. Process selection therefore often involves finding a suitable compromise, in which cost plays an important role.

Pahl and Beitz[5] divide the design process into four basic stages as shown in Figure 1. The overall manufacturing process selection usually has to be done just before or during the embodiment design stage, preferably in a concurrent engineering context. Manufacturing process choices made at this stage

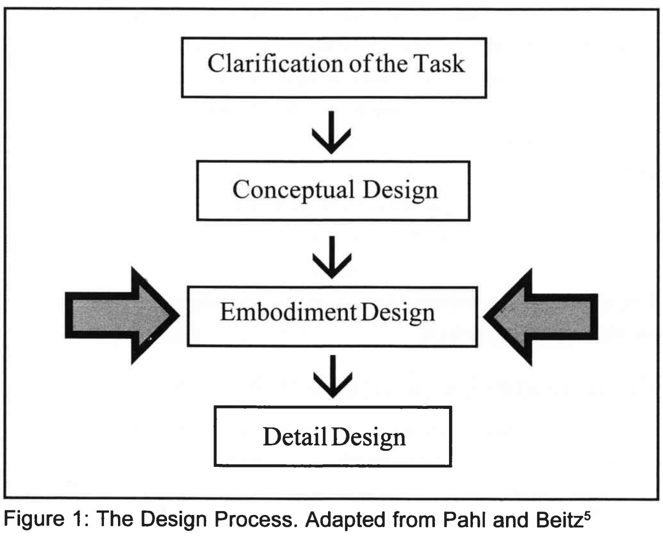

Figure 1: The Design Process. Adapted from Pahl and Beitz[5]

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are expensive to change later, often requiring substantial effort in redoing detail designs of parts and assemblies, and may even extend to reworking process and production planning. It is therefore extremely important that sound process choices be made as early as possible.

Cost estimation during the early design stages is complicated by the lack of product information available. Typically, after the concept development stage and during the preliminary embodiment design (or layout design) only rough sketches with the principal dimensions are available. In spite of these challenges, the role of manufacturing cost estimation within the design for manufacturing (DFM) paradigm is well recognised. Leibl et al.[6] showed that designers not using a cost estimation tool during the early design phases, created products that are up to 80% more expensive than the design of their counterpart who used a cost estimation tool. They also observed that the designer not using a cost estimation tool took 40-50% longer than their counterparts using the cost estimation tool. This clearly indicates that cost estimation during the early phases of design can help to eliminate infeasible concepts quickly, so that designers can focus on the more cost effective concepts.

A very important aspect of cost estimation is that it must give the designer feedback to optimise a part's design for particular processes (Feng et al.[7] and Eskilander[8]). The designer must know what the cost drivers are, which features of the design carries the most cost and what, if anything, can be done to reduce the manufacturing cost. This information, combined with the appropriate design rules, must guide the designer to minimise the manufacturing cost and meet the cost target.

Despite the convincing arguments for advantages of cost estimation in the design phase, there is a remarkable lack of published data and models. Some of the studies relevant to fabrication processes that were published are the following: Boothroyd, et al.[9] published cost estimation models for various high-volume processes, but with little attention to fabrication processes. Esawi and Ashby[10] developed a system that helps designers to eliminate infeasible manufacturing processes and it also prevents them from overlooking potential processes, but works at a high level of abstraction. Farkas and Jármai[11] describe a cost model for welding that they use for product optimisation, but they ignore the other fabrication processes such as bending, cutting, etc. Maropoulos et al.[12] describe a system for fabrication process planning in the early stages of design, but they do not describe the model used.

Publications often do not state what production environment their models are aimed at, even though cost estimation is strongly production context sensitive. For example, a cost model developed for a mass production environment cannot be used for products manufactured in job shop or small lot size environment.

The value of cost estimation models during early embodiment design is therefore clearly established, but no models applicable to the small production volume fabrication environment were found in the literature. This lead to the development of the models presented here.

Cost Model Development Approach

The models presented here follow a times and rates approach to cost estimation. This method is intuitive to develop and interpret and it is a very popular approach in industry according to Eskilander[8]. The data was gathered by Maree[1], Schuster[2], Schreve[3] and De Swardt[4], through time studies using a video camera or stopwatch. It was explained to the artisans that the data would be used for academic purposes. Still, the taking of times certainly affected the productivity of the artisans, especially when doing video recordings. For one batch of welded assemblies, the last assembly was recorded with video camera and the welders worked notably faster – maybe to show off their skill! Unfortunately this can distort the cost models. However, the data was gathered over long periods and at four different facilities. It is the authors' opinion that the sheer amount and diversity of the data countered the effect that the measuring of times had on the productivity. Therefore, the authors conclude that any effect that the recording of times had on the productivity of the artisans does not significantly decrease the accuracy of the cost models, particularly when the wide variability in measured costs is taken into account.

Due to the nature of a small production environment, with much manual labour, the recorded times are very variable. There often were a few parts in a batch that took significantly longer to manufacture than the rest of the parts. During the assembly of the parts this was often caused by parts that did not fit properly in the assembly. These times tend to pull the average time of the batch unreasonably high. This presented difficulties in the analysis of the data and development of the cost models. After consultation with an expert statistician, it was decided to use median values rather than average values and a robust regression statistical method (Hoaglin[13]) rather than least squares regression. In this way the cost model does not penalise the design for bad production practice.

In the cost models presented here, reasonably efficient production is assumed. It is the authors' opinion that a design must not be penalised for inefficient production settings. A design should however be penalised if some features cause inefficient production. One of the reasons for doing a thorough cost estimation is to identify such aspects of a design. The researchers therefore used their judgement to discern situations where cost increases could be attributed to poor production practices and to lessen these effects on the cost models.

Preliminary cost models were published by Maree and Basson[14], Schreve et al.[15], and Basson and De Swardt[16]. The data and models from this research were combined into one set of models and presented here. The most challenging part of developing these new models is the integration of De Swardt's[4] models with the rest of the data. He did his time studies on the manufacture of heavy earth moving equipment, typically dragline buckets with a capacity of up to 168 m^3. The rest of the data was collected for assemblies weighing less than 200 kg.

Cost Models

Models for flame cutting, bending, tack welding and welding assembly are presented here. As indicated above, a time and rates approach was used. The cost models therefore relate the manufacturing time to cost drivers, or manufacturing features, on the parts. The estimated times have to be multiplied by suitable respective rates to give cost estimates. Since the cost models are aimed at small production volumes, set-up times (i.e. costs incurred once per batch) play a significant role and are given separately.

Flame Cutting

Flame cutting is the operation where parts are cut from sheet metal using a blowtorch. The material is mounted on the machine bed and not moved until all the parts are cut. All the data gathered for flame cutting operations integrated very well.

In the model presented here, a variable m_{hand} is used. This is simply a boolean variable indicating whether the part is handled manually or with a lifting aid such as an overhead crane. According to Corlett and Clarck[17] parts weighing less than 21kg can readily be handled manually. Note also that all the models for flame cutting operations are valid for mild steel sheets up to 200mm thick.

The set up time includes the time to prepare the machine for operation and clean it afterwards. The set up time per part is:

$$t = \frac{1}{n_b}\left[688\left(1 - m_{hand}\right) + 440 m_{hand}\right] \qquad (1)$$

The time to load the material is a function of the number of parts that fit in one sheet and the area of the raw material. The raw material area is normally not determined by the designer, but by the production planner. However, sheet metal normally comes in standard sizes and it should therefore not be difficult to make a reasonable estimate of the material area. Note that the time must be reduced not by selecting smaller sheets, which will result in more handling time, but by designing parts for the optimum nesting, since the time is divided by the number of parts per sheet. The loading time is:

$$t = \frac{1}{n_s}\left[253\left(1 - m_{hand}\right) + \left(15.27 A_{material} + 3.59\right) m_{hand}\right] \qquad (2)$$

For each cut made with the flame cutter, the flame must first pierce the material before it can start cutting. This is called piercing time. Obviously the designer must try to keep the number of cuts a small as possible. One piercing operation is done for the outside profile of a part and one per hole. This time and the cutting time both increase with the material thickness. Some flame cutters used in the factories where the case studies were done, have four nozzles, therefore the piercing and cutting time per part decreases if two or more parts can be cut simultaneously. However, this is a production parameter over which the designer may not have control or knowledge of. It is therefore recommended that, unless other information is available, the designer must assume that the parts are cut one at a time, thus assuming that $n_{nozzles}=1$. The piercing time is:

$$t = \frac{1+n_{holes}}{n_{nozzles}}\left(1.96 t_w + 14\right) + 11 t_c\left(1+n_{holes}\right) \qquad (3)$$

The equation for cutting time is a least squares regression through table data given by the nozzle suppliers. Times measured by De Swardt[4] were slower, but this may have been due to inefficient production practices. The cutting time is directly proportional to the aggregate length of all the cuts.

$$t = \frac{60 L_{cut}}{\left(946.46 t_w^{-0.3901}\right) n_{nozzles}} \qquad (4)$$

The unloading time is the time it takes to remove all the parts and scrap from the machine bed. For the large parts, considerable time is spent to remove scrap material from the bed, since this is also done with a mechanical aid. The unloading time is:

$$t = 13.9 m_{hand} + [65 + 98(1 + n_{holes})](1 - m_{hand}) \qquad (5)$$

A grinding operation normally follows flame cutting. De Swardt[4] provides a separate model for this.

Bending

The principal difference between the models of De Swardt[4] and Schreve[3], is that the former models were developed for a 1250 ton press, bending material between 6 and 50 mm thick, while the latter models are for a 4 ton press bending material no more than 6 mm thick. By integrating the models, handling operations with mechanical aid is now included. The cycle time for the two press brakes differ significantly. The gap is bridged by incorporating data published by press brake manufacturers. They provide approach speed, bending speed, return speed, stroke length, motor power and bending force for each machine. The bending force required to make a specific bend can be calculated in terms of the length of the bend, the material thickness and the bend angle. Although bending angle is included in this equation, it must be remembered that bending is done in standard dies, so the designer can minimise the angle, but should keep to the standard angles. Schreve[3] did observe the bending of non-standard angles. In these instances, the stroke length of the press was changed so that it did not press to the bottom of the die. In these cases the set up time is longer, since the adjustment of the stroke length is a trial and error process.

The equation for the set up time includes the time to do a die change (1467 seconds). If all the bends on a part is for the same angle, the die is not changed. This quantifies the design rule that the number of different bend angles must be minimised. The additional terms in the set up time equation are for operations such as setting the stops and preparing the machine. This is added per bend. The set up time is:

$$t = \frac{1}{n_b}\left(\frac{1467}{n_{angles}} + 565 n_{std\_angles} + 831 n_{nstd\_angles}\right) \qquad (6)$$

The loading and unloading time must be added per bend that is made. Schreve[3] found that for parts handled manually, the time depends mostly on the part's projected area. The loading and unloading time is:

$$t = [(25.8 A_{part} + 5.5) m_{hand} + 98.5(m_{hand} - 1)](n_{std\_angles} + n_{nstd\_angles}) \qquad (7)$$

The cycle time per part, as discussed above, is:

$$t = (0.05 L_b t_w \theta_b + 0.67 t_w + 2.8)(n_{std\_angles} + n_{nstd\_angles}) \qquad (8)$$

Note that the bending operation times are only valid for sheets up to 50mm thick.

Tack Weld Assembly

A new model for tack weld assembly had to be derived from the data collected by De Swardt[4] and Schreve's[3]. Note that Schreve's model already incorporated the data of Maree[1] and Schuster[2]. Simple integration of their models is not possible, since the models use different design parameters for cost estimation. The parameters are summarised in Table 1.

The integration led to the regression formula given in equation (9).

$$t=a_1+S\theta+a_2SF+a_3t_wL_jB_{sheet}+a_4m_{part}n_w+a_5t_{fd}c_a+a_6t_wL_jn_w+a_7 \quad (9)$$

De Swardt's[4] Model	Schreve's[3] Model
Mass	Mass
Total length of Joints	Total length of Joints
Material Thickness	Size **
Number of Welded Joints	Symmetry
Existence of In-plane Curvature	Existence of Critical Alignment with other parts
	Flexibility of Part
**The definition given by Boothroyd et al.[9] for manual assembly is used here	

Table 1: Comparison of Assembly Model Parameters

Equation (9) was derived by testing the significance of various parameter groups using the F- and t-statistics (Walpole and Myers[18]). The parameter groups given in this equation are the ones remaining after various other groups were shown to be insignificant.

The equation shows that the assembly time depends on the size and symmetry of the parts (Boothroyd et al.'s[9] definitions for size and symmetry are used). The symmetry affects the orientation time of each part. The size is used to scale the effect of this symmetry for parts of different size since parts of larger size will clearly take longer to orientate.

The orientation time also depends on the flexibility of the part. Here, flexibility is only a boolean variably, i.e. it will be 1 if the designer considers that the part is flexible. Again, size is used to scale the contribution of flexibility.

The third group of parameters reflects the time to join sheet metal parts, normally in a butt weld configuration. It was found that the length of the joint and the material thickness determines the time to assemble parts in this configuration.

It will take longer if there are more contact surfaces that must be aligned before welding can commence. This is reflected in the fourth parameter group. In this case it was found that it is best to scale the effect of the number of contact surfaces with the part mass.

Critical alignment with other parts outside the welded assembly requires special attention during assembly, e.g. a pin might be driven through a hole in a part to ensure that the hole is correctly positioned for a shaft passing through it. Critical alignment is determined by location tolerances in the design. Here, critical alignment is a boolean parameter. If any special tolerances exist, this parameter must be 1. Since the part will already be roughly positioned in the jig, the part size or mass cannot be used to scale the fastening time. Rather, the principle dimension of the feature that must be aligned is used. In the case of the pin and hole example mentioned here, the diameter of the hole is used.

Parameter	Value
a_1	0.0003
a_2	-0.1716
a_3	0.0043
a_4	0.1358
a_5	-6.3877
a_6	0.0006
a_7	223.8
R^2	0.778

Table 2: Coefficients of Equation (9)

Finally, the actual tack welding time depends on the length of the joint, the number of contact surfaces and the material thickness. Since the parts are positioned in a jig, it is not necessary to scale this parameter group any further.

The F-statistic for this correlation is well above the critical value (50.4 vs F-critical 2.22) showing that there is a good statistical relationship between the chosen parameter groups and the observed times. Also, the t-statistic for each term is above the critical value indicating that each term is statistically significant.

However, while this equation gives some valuable insight into the importance of some of the design parameters, and despite the good statistical relationship, it is unfortunately not a very good model. The constant of this equation implies that the assembly time of most parts will be at least 223 seconds. This over estimates most of the parts studied by Schreve[3]. Furthermore, the model in this form predicted negative times for some parts. Forcing the constant to be zero did not improve the situation.

The hypothesis that the assembly time is linearly related to the design parameters was discarded and a power law regression model was derived. Again, insignificant parameters were eliminated using statistical analysis. Interestingly it was found that the best correlation, in terms of the observed statistical parameters (R^2, F- and t-statistics) was obtained by using only the part mass and length of the joints. The F-statistic for this correlation is 229.4 vs. the 50.4 observed for the linear correlation given above. The assembly time is:

$$t=17m_{part}^{0.369}L_j^{0.249} \quad m_{part}<13190\,\text{kg}, L_f<5253\,\text{mm} \quad (10)$$

Note that the time in equation (10) is the time per part in the assembly. Thus, the number of parts per assembly is implicitly also a cost driver.

The R^2 statistic of the regression is 0.836, somewhat better than the regression result for equation (9). While this equation is simple to use and gives a good result, it does not provide much design insight. The attempt at integrating the models for assembly basically showed that cost estimation is very domain dependent. This is illustrated by the fact that the average mass of the parts studied by Schreve[3] is 3.96 kg and those of De Swardt[4] is 554 kg. Furthermore, in the factories where Schreve[3] did his time studies, jigs are used extensively and parts are assembled in batches of 20 or more. In De Swardt's[4] case jigs are used much less due to the sheer size of the parts and the very small production volumes. It is therefore the authors' opinion that a model such as equation (10) be used for preliminary cost estimation only, typically during process selection as suggested by Esawi and Ashby[10]. The model is ideally suited for this purpose since it requires only a rough idea of what the part will look like in order to estimate the mass and length of the joints. Together with knowledge of the number of parts in the assembly, a reasonable estimate of the cost can be obtained.

Equation (10) was derived from time measurements for 93 different parts. In the instances where time studies were done for batches of more than one parts, the median time for the batch was used to derive the regression formula. Then, statistical tolerance limits were derived. The result of the statistical analysis is given in Table 3 and the measured and estimated times are compared in Figure 2. The error is the ratio of difference between the estimated time and the measured time to the measured time, expressed as a percentage.

Minimum Value	-77.40%
Maximum Value	301.35%
Sample Size	93
Mean	19.44%
Standard Deviation	75.60%
Lower Limit	-123.36%
Upper Limit	162.25%

Table 3: Summary of Assembly Error Distribution

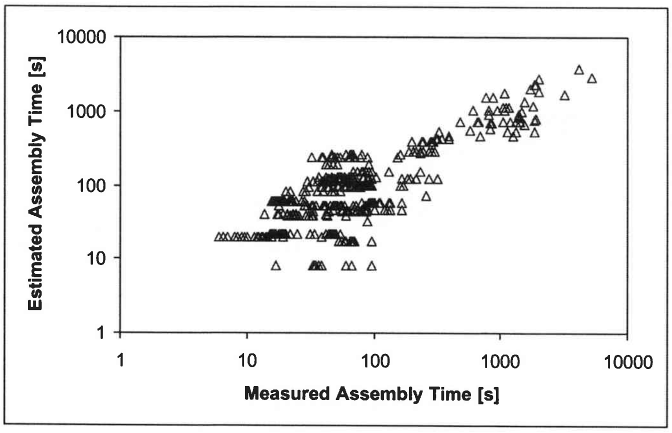

Figure 2: Comparison of Assembly Time Estimate and Measured Times (Note that logarithmic scales are used on both axes)

Final Welding Time

A final welding step follows the tack weld assembly. Often the assembly is taken out of the jig and welded elsewhere. Here, De Swardt's[4] model for welding is simplified so that it is suitable for use during the early stages of embodiment design. His original model requires that the designer must have knowledge of the welding electrode that will be used. By using average values of the electrode parameters, the welding time is

$$t=\frac{L_j}{14.6}Round\left(\frac{A_{weld}}{25}\right)+16RoundUp\left(\frac{L_j}{833}\right)+0.0788A_{weld}L_j \qquad (11)$$

The equation is derived with the average welding parameters for 1.6mm flux core wire. It includes the arc time as well as fettling time, repositioning time and electrode change time. Equations for other welding processes such as MIG or TIG welding will have the same form; the constants will simply be different. These constants can be derived by using De Swardt's[4] model and substituting the relevant average process parameters. So, if the designer knows beforehand which welding process will be used, he/she can change the welding parameters as required. However, the equation in its current form for flux cored welding already gives good time estimates even if other welding processes are used. This will be demonstrated in the case study. In the case study, SMAW and MIG welding were used, but the time estimates were done with equation (11). Schreve[3] gives correlations for SMAW and MIG welding.

Accuracy Issues

Many cost models reported in the literature claim that it can predict the cost to within 10% or even better. However, the experience of the authors is that in the small production volume environment, such high accuracy cannot be expected. For example, in one batch of seven welded assemblies, the tack weld assembly time varied by more than 30% from the average time. The reason is that in a small production volume environment, most of the work is done manually. The artisan is also often required to plan the job and interpret the drawings. Often parts that do not fit in the assembly are reworked immediately instead of rejecting them, as might be the case in a mass production environment. Furthermore, in very large batches irregularities in the production time are averaged out so that the aggregate time for the batch will be very close to the estimated time.

Thus, it is the authors' opinion that cost estimation in a small production volume environment cannot be as accurate as cost estimation in a mass production environment. Uncertainty in the estimated costs of about 30% is probably typical.

Case Study

The cost models presented here, together with cost models for other processes reported by Maree[1], Schuster[2], Schreve[3] and De Swardt[4], were incorporated in a computer program. With this program the user builds an assembly tree of the project and adds the relevant fabrication processes (this can be considered to be a concept process plan, suitable for manufacturability assessment during early phases of embodiment design). The input parameters for the cost estimation models are calculated and entered by hand. This program was used to do the case study reported here. The program uses the simplified assembly model presented in equation (10).

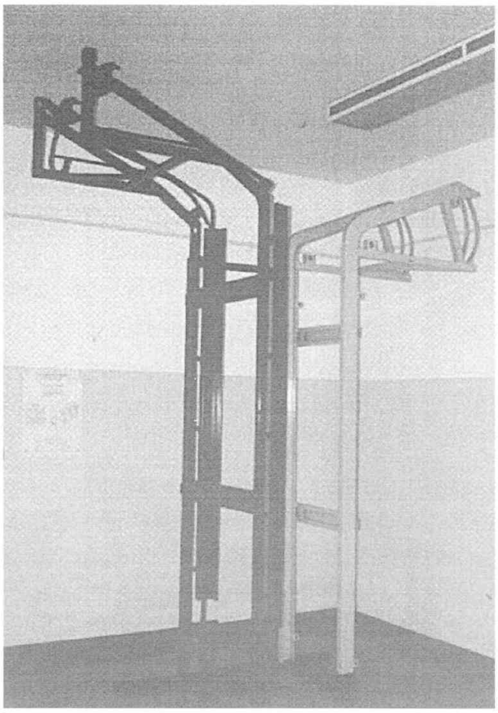

Figure 3: Side Loader Assemblies

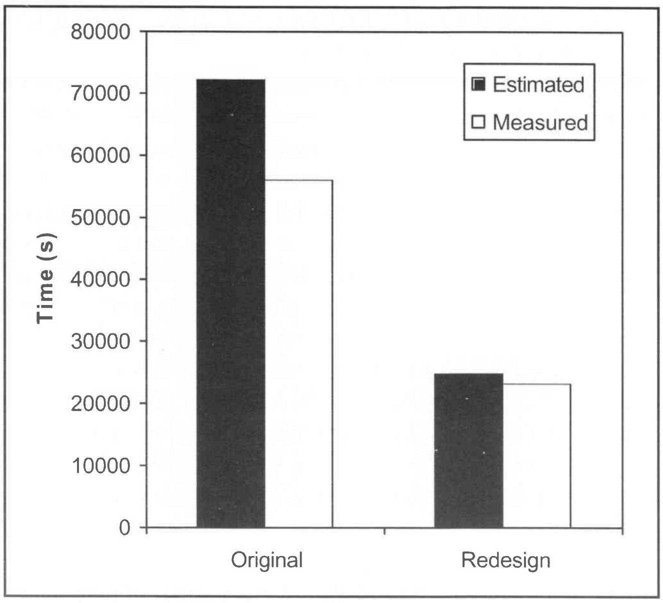

Figure 4: Comparison of Fabrication Times

In order to validate the cost estimation models presented here, the fabrication time of two side loader assemblies (Figure 3) are compared with the time estimated using the new cost models. The first side loader consists of 99 parts and weights 130kg. Maree[1] redesigned the side loader and applied the Design for Assembly rules. The redesigned side loader has 41 parts and weights 121kg. He also measured the fabrication times for both assemblies.

The total predicted fabrication times are compared with the measured times in Figure 4. The times are over estimated by 28% and 7% respectively. It is also very interesting to note that the reduction in fabrication time observed for the redesigned side loader is proportional to the reduction in the number of parts of the assembly.

It took 4h 27min to do the cost estimate of the original design and 1h 40min for the redesign. It took less time to estimate the cost of the redesigned side loader because it consists of fewer parts and because some of the parts are common to both assemblies and thus it was not necessary to repeat their estimates. Most of the time goes into calculating the input parameters, such as the mass of the part, section areas, etc. Many of these parameters will be readily available if CAD drawings of the parts were available – which may not necessarily be the case during embodiment design. This was not the case here. Also, if the cost estimation software were linked to a CAD system, the data input time can be reduced significantly. Liu and Basson[19] did such an implementation.

Although the side loaders were assembled using SMAW and MIG welding, the assembly model still gives reasonable results. The assembly model was developed from data for MIG, SMAW and FCAW. In this instance it was a safe simplification. However, the validity of this must be investigated for a large sample of case studies. The reality is that the designer may not know which process will be used and will therefore anyway have to make an assumption. A case study reported by Farkas and Jármai[11], shows that the optimal dimensions of a welded assembly do depend on the applied welding method.

Conclusions

In this paper cost estimation models, using a times and rates approach, are presented for fabricated assemblies made in small production volumes. The models are intended for use in the early embodiment design phase and therefore only parameters readily available to a designer at this stage are used in the models. The models can help the designer to optimise the design for fabrication cost since it links the cost to the design parameters. It can be used to help the designer in selecting an appropriate manufacturing process if the cost estimated with these models can be compared to the manufacturing cost of alternative processes. The fabrication time of two assemblies were estimated with accuracy commensurate with a small production volume environment. This result was achieved with a very simplified assembly model, which can be applied to parts weighing between a few hundred grams and five ton.

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