TECHNICAL COST MODELLING FOR A NOVEL SEMI-SOLID METAL (SSM) CASTING PROCESSES FOR AUTOMOTIVE COMPONENT MANUFACTURING

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The cost structure and benefits of a new billet preparation process in semi-solid metal (SSM) casting of automotive components were investigated. The process was developed by the CSIR, a government research and development agency in South Africa. It has been well established that over 70% of the total development cost of a product and its manufacturing process is decided during the design phase, although this phase accounts for less than 7% of the total costs. It is thus important to be able to predict the cost structure of a newly developed manufacturing process if it is to be considered by manufacturing enterprises for development to substitute a process that is in use.

The cost of the new SSM technology was established by technical cost modelling and was compared with the cost of two competing technologies, forging and die casting. The cost model was developed in a spreadsheet using engineering models, data from literature and information provided by process experts. Estimated engineering costs were classified accordingly as accounting costs. The developed costing model was used to estimate and analyse the total manufacturing cost for each manufacturing process, and to study how total cost is affected by other variables such production volume, cost type, etc.

It was found that depending on the type of component and on production volume the CSIR SSM process can compete on cost with die casting and hot forging. It was also found that improvement in the cost competitiveness of the CSIR SSM manufacturing process can be achieved by reducing material usage during manufacturing by reducing the diameter of the runner and sprue system.

Keywords: Casting, forging, technical cost modeling, automotive industry, manufacturing process, semi-solid metal casting, SSM.

Introduction

In the manufacturing industry, shareholder value is created by manufacturing of products that have a higher selling price than the costs incurred in the manufacturing process i.e. by creation of product value. Product value (in the form of shape, functionality and/or improved product-material characteristics) is added to the material, components, or sub-assemblies (work-in-process) during a manufacturing process. The value-addition proposition presumes that the customer is willing to pay for the changes that are imparted to the component or product during the manufacturing process. From a customer's perspective, the manufactured product must be of the required quality and functionality and must be available in the required quantity at the required time. The manufacturing processes that are selected to manufacture a product must be able to satisfy customer's demands.

From a manufacturing enterprise perspective, the manufacturing value-chain must be profitable. The total cost associated with the processes that are used inside the manufacturing enterprise to produce the product must be less than the total revenue from sold manufactured products by the margin required for economic viability of the business.

It is important that a manufacturer select manufacturing processes that can support the required profitability, while at the same time satisfying the customers' requirements of cost, quality and production volume. The process of selecting the appropriate manufacturing process is a complex task due to multiple manufacturing processes that can be used to achieve similar results. For example, metal components that have complex shapes are normally manufactured using casting technology. There are many casting technologies that must be considered such as sand casting, die casting, investment casting, semi-solid casting, etc. Sometimes, the same product can be made by other manufacturing processes such as forging, machining, etc.

The aim of this work was to develop a cost model for a novel billet preparation process in semi-solid metal (SSM) casting that has been developed by the CSIR, South Africa. The CSIR SSM process is compared with selected die casting and forging. The research presented in this paper is limited to automotive component manufacturing and selected metals (aluminum, copper, magnesium and zinc). This information was required to enable Original Equipment Manufacturers (OEMs) in the automotive industry to assess the CSIR technology for application in automotive component manufacturing. At the time of writing the technology was in an industrial testing phase with a South African casting component supplier as well as an automotive OEM.

In automotive component manufacturing the SSM process is suitable for light weight performance or safety critical components such as brake master cylinders, rocker arms, brake calipers, pulleys, engine brackets, clutch cylinders, power steering valve boxes, fuel rails,

suspension arms, pistons, motor housings, wheels, oil pump housings and belt covers (Ivanchev et al., 2006). Automotive components that were used in this study were taken from NADCA (2006) as depicted in Figure 1.
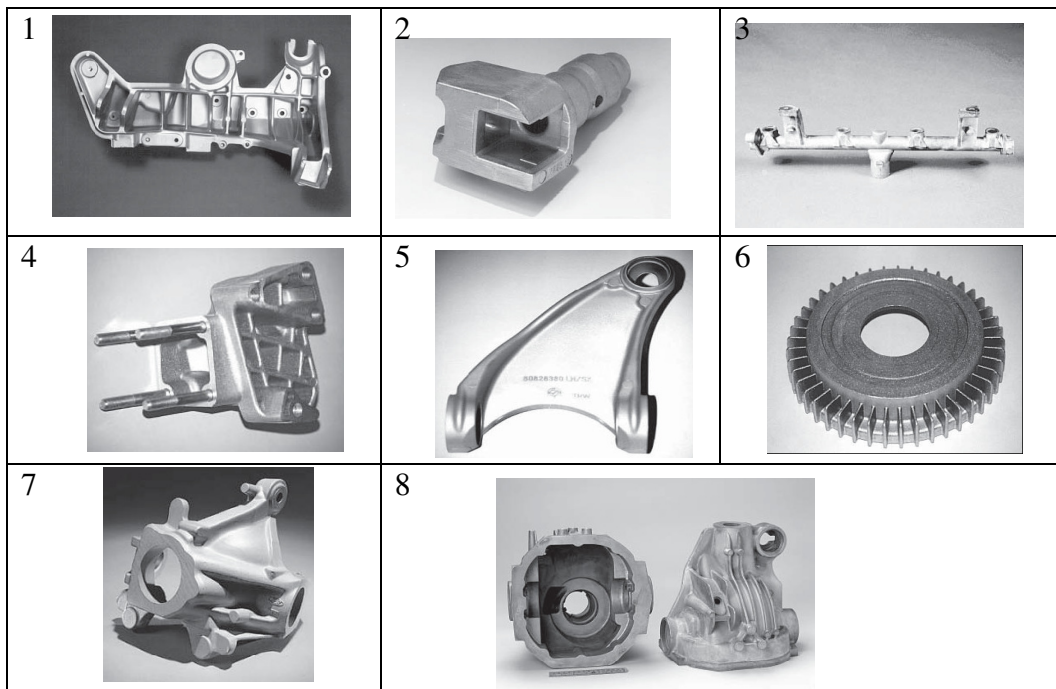

Figure 1. Eight components used in this study (Source: NADCA, 2006).

Cost modelling is important during the development of the product, or during the technological development of a new manufacturing process for the following reasons:
- for competitive bidding, and
- for evaluating the effect of technical decisions, or other alternatives on the economics of a product.

Most costing systems cannot achieve the latter, as this requires knowledge about the manufacturing process and accounting systems. It is important for technology developers in developing countries such as South Africa to prove the economic benefits of their newly developed technologies if these technologies are to be licensed to multi-national corporations (MNCs) that have the capacity to supply the global market.

Figure 2 shows cost drivers for manufacturing processes in the form of a cause and effect diagram.
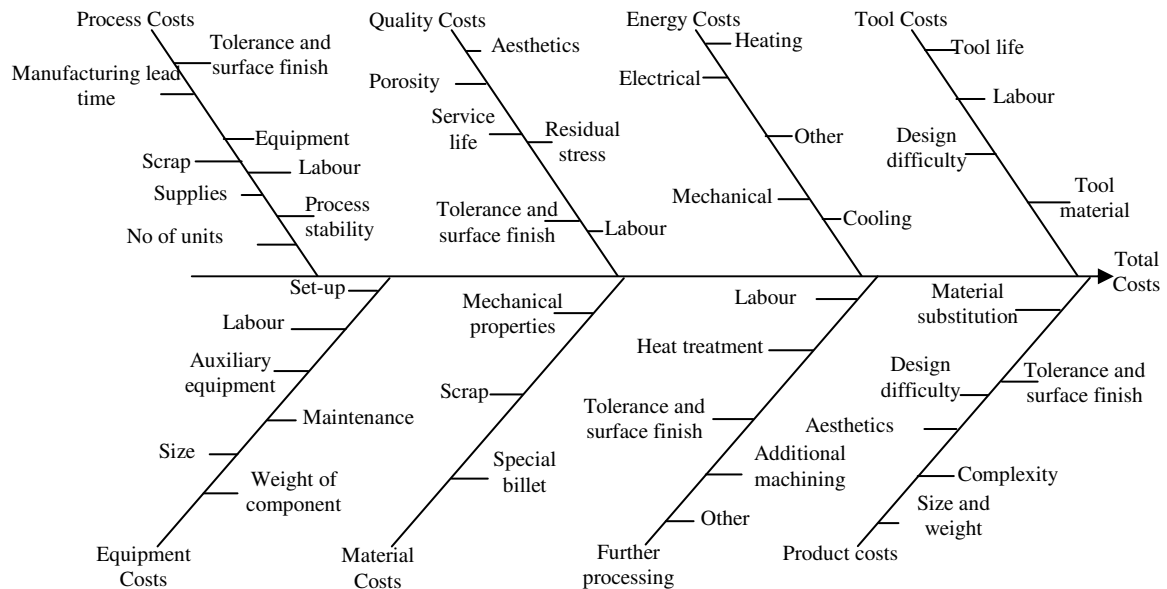
Figure 2. Cause and effect diagram depicting costs drivers for manufacturing processes.

Design for Manufacturing philosophy

Engineering design and manufacturing are interrelated tasks. In the past, they used to be viewed independently of each other. Each component or product must be designed so that it not only meets design requirements and specifications, but also can be manufactured economically and efficiently. This approach improves productivity and allows a manufacturer to remain competitive. (Kalpakjian, 2000)

Design for manufacturing (DFM) is a philosophy which takes this view of the design and manufacturing tasks of engineering products/components. It is a comprehensive approach to production of goods, and it integrates the design process with materials, manufacturing methods, process planning, assembly, testing and quality assurance (Madan et al, 2006). This requires that designers have a fundamental understanding of the characteristics, capabilities and limitations of materials, manufacturing processes and related operations, machinery and equipment. This knowledge includes characteristics such as variability of machine performance, manufacturing process, dimensional accuracy, surface finish of work-pieces, etc.

Designers must be able to asses the impact of design modifications on manufacturing-process selection, on assembly, inspection, tools and dies, and product costs. Establishing quantitative relationships is essential in order to optimise the design for ease of manufacturing and assembly at minimum product cost. (Kalpakjian, 2000). The aim of this project was to

develop a cost model that could be used to determine the effects of different technical decisions on the cost of an automotive component. The cost model had to be able to compare the different casting and forging manufacturing processes. It also had to be able to be interpreted by people who use normally accepted accounting principles for making decisions.

CSIR's SSM Manufacturing Process

CSIR's SSM process implements an innovative billet preparation technique that results in cycle times of 1 component/minute. It uses raw material, in the form of aluminium (alloy A356), which is melted and poured in a stainless steel cup. The cup with molten material is then placed in a magnetic induction electric furnace, where it undergoes controlled cooling until semi-solid. The alternating magnetic field in the furnace adds heat to the metal by imparting vibration energy to the atoms/molecules of the metal/alloy. The temperature difference on the surface of the semi-solid metal billet in the stainless steel cup is controlled to an accuracy of 1^0C. When the temperature has stabilised, the stainless steel cup with semi-solid metal is placed in a high-pressure die casting machine. Pressure is then applied to the semi-solid metal in a die cavity. The stainless steel cup is reusable. However, it is provided with an aluminium disk at its base which is consumed during die-casting.

Technical Cost Modelling

Costs estimation tools can allow development engineers to determine the commercial viability of various designs as well as compare alternative designs based on costs. Allowing the designer to establish the relationship between costs and design decisions is the most important function of cost estimation tools. If a cost estimation tool is used in the early design stages of the product/component, cost can be a constraint that the designer must design to, thus limiting options. If a cost estimation tool is not used in the early design stages, cost analysis that is performed later can cause designs to required rework (Noble and Tanchoco, 1990), (Field et al, 2001). Correcting design is more costly than correctly designing a product in the first place. (Johnson, 2004)

A technical cost model must be able to classify costs using commonly accepted accounting criteria. The reason for this is that costs incurred by the firm must be reported using accounting systems. Moreover, decision makers in a firm normally use accounting data to make decisions. A widely accepted costing method is activity based costing (ABC). It classifies costs using normally accepted accounting rules.

Activity-based costing allows tracing of costs to their cost drivers, similar to those depicted in Figure 2. A range of activities are taken into account that are required to deliver a product. The costs of these activities are assigned to the range of products that a company

manufactures based on the product's usage of the activities. Some of the documented advantages of an activity-based cost modelling are:

- It can be used to determine product profitability, thus allowing decision makers to determine which products should be kept, expanded or dropped (Cooper and Kaplan, 1988),
- It can be used toimprove a company's profitability (Cleland, 2001), and
- It allows decision makers to identify the best opportunities for improvement and learning (Cooper and Kaplan, 1991).

Thus, a technical costing tool or model that is used, or developed, must be able to meet the advantages provided by the ABC method.

Technical or process-based cost modelling is a generative cost estimation technique. It analyses the economics of manufacturing by relating component characteristics to engineering and manufacturing quantities. These quantities are then used to determine the manufacturing costs of the component. It can be used to determine manufacturing costs early in the design process. It is used to decompose the manufacturing costs for several manufacturing processes into detailed elements of both fixed and variable cost categories. Process-based cost models are constructed by working backward from cost – the model's objective- to physical parameters that can be controlled – the model's inputs. The modelling of cost involves correlating the effects of these physical parameters on the cost-determinant attributes of a process and then to relate these attributes to a specific cost (Kirchain and Field, 2001). The relationship between physical parameters and cost-determinant attributes is determined either by using physical relationships or through statistical analysis. Process-based models fulfil the requirements mentioned above. (Johnson, 2004)

The value of process-based cost modelling arises from its ability to detail the major driving factors of costs, as well as its ability to categorise these costs (using normally accepted accounting rules and relating costs to engineering activities). This categorisation is rare in predictive costing tools, and allows decision makers to calculate the cost and benefit of trade-off options that merit more in-depth analysis. (Johnson, 2004)

Technical-cost or process-based models require information about several aspects of a component to be manufactured e.g. minimum and maximum wall thickness. Thus, they are full models, and are only useful when such information is available. They are also useful for detailed analysis of cost of components. Scaled down methods have been developed, and are used mainly for product manufacturing costs. These methods are suitable for cost analysis of many components. (Johnson, 2004) The work in this project is only concerned about components' manufacturing costs. For this reason, technical cost modelling has been selected for this project.

The cost estimation tool should be suitable to analyse and present quantifiable information to allow the decision maker to process or integrate uncertain or incomplete information throughout the design process (Noble and Tanchoco, 1990). The ability to accurately predict costs at each stage of a development effort has been described as being at the core of competitive manufacturing (Wei and Egbelu, 2000). The goal of technical cost modelling implemented in this study is to determine the costs of a process or product before it has been manufactured. (Johnson, 2004)

The technical cost model developed in this study is suitable only for the study of the economics of a single manufacturing process. In order to study the economics of manufacturing when multiple manufacturing processes are required to manufacture a component, other methods have been developed and should be used. These methods however require that the information about the other processes involved in the manufacture of a product/component be known.

Development of Technical Cost Model

The technical cost modelling developed in this study was designed to achieve comparative cost analyses of selected casting and forging manufacturing processes. It is comprised of five steps (Figure 3). The model is implemented in a spreadsheet. The effects of the different technical decisions on the economics of the manufacturing processes for a particular component are quantified individually in Steps 1 and 2. In Step 3, these costs are classified into fixed and variable costs by using standard accepted accounting rules. This is important in order to compare the new manufacturing processes with the old/current/competing manufacturing processes. It also provides the decision maker with the insight of cost break-downs. Figure 4 shows how the different parameters are used during the cost estimation process.

In Step 3, the input variables from Step 1 and the manufacturing processing variables from Step 2 are used to estimate the cost of manufacturing a component using the selected manufacturing processes. The following accounting costs are estimated: fixed cost per component (C_F), variable cost per component (C_V) and total manufacturing cost per component (C_T).
Step 4 involves the presentation of the results from Step 3 in the form of easy-to-interpret graphs. Moreover, if results for a competing manufacturing process are available, the economics of the new process can be compared with that of the competing manufacturing process/processes.

Finally, in step 5, the sensitivity of the different parameters identified in Steps 1 and 2 can be analysed. The effects of different technical decisions can be analysed in more detail by conducting sensitivity analyses. The advantage of implementing the model as presented in

this study is that sensitivity analysis can be readily conducted on spreadsheet software and a knowledge-based tool can be implemented as well.
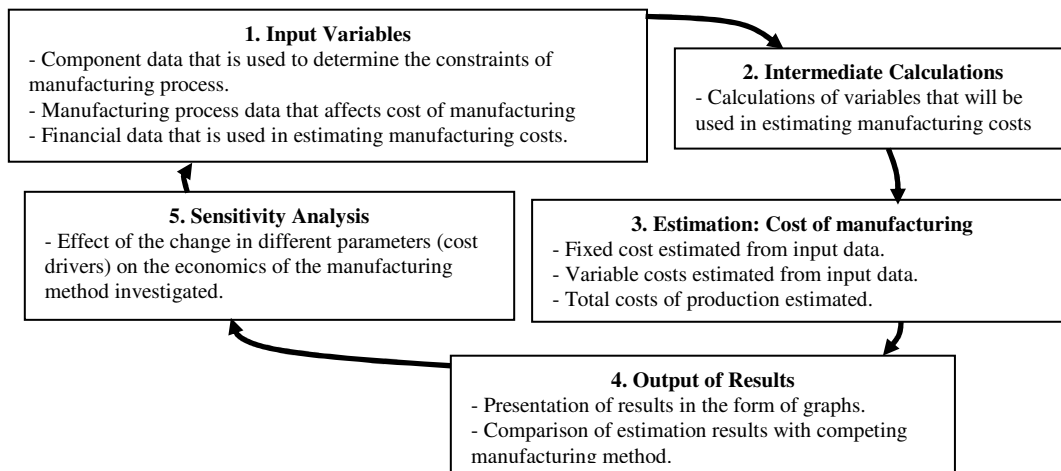

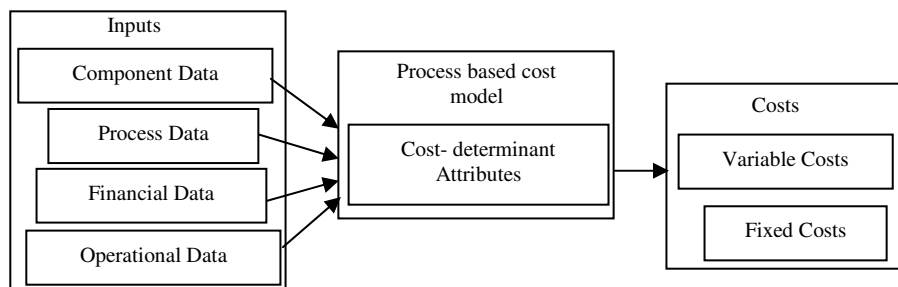**Figure 3.** Steps in technical cost estimation model developed.

Figure 4. Data flow and processing in technical cost model developed.

Cost Estimation

Total manufacturing costs (C_T) per manufactured unit are the sum of total variable costs (C_V) and total fixed costs (C_F), i.e.

$$C_T = C_V + C_F \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \quad (1)$$

Total variable cost per manufactured unit is the sum of total raw materials costs per unit (C_{Matr}), total utilities costs per unit (C_{Ut}), total costs of inserts/other consumables per unit (C_{Ins}), and total costs of in-mould coatings per unit ($C_{M.C.}$). The total costs above are based on yearly production volumes of the required component, *n*.

$$C_V = C_{Matr} + C_{Ut} + C_{Ins} + C_{M.C.} \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \quad (2)$$

Total fixed cost per unit is the sum of the following costs; total costs of main machines per unit ($C_{M.M.}$), total costs of tools per unit ($C_{T.C.}$), total installation costs for both main machines and auxiliary equipment per unit (C_{Inst}), total costs of maintenance for main and auxiliary equipment per unit (C_{Maint}), total costs of building(s) in the form of floor space costs per unit (C_{Bld}), total cost of auxiliary equipment per unit (C_{Aux}), total overhead costs per unit (C_{Over}) and total costs of capital recovery per unit (C_{CapR}). The total fixed costs per unit are also dependent on the total annual requirement of components. Total direct labour costs per unit ($C_{D.L.}$) were taken as a fixed cost as it was assumed that the labourers have permanent work contracts with the manufacturing enterprise. If the demand is more than the annual capacity of the manufacturing setup, then fixed costs become steps costs.

$$C_F = C_{M.M.} + C_{T.C.} + C_{D.L.} + C_{Inst} + C_{Ma\,int} + C_{Bld} + C_{Aux} + C_{Over} + C_{CapR} \dots\dots\dots\dots (3)$$

Manufacturing Process Variables

Manufacturing process variables are dependent only on the manufacturing process that is used to manufacture a part. For example, the life of a tool used for SSM casting is greater than that of the tool used for die casting due to high thermal stresses caused by high operating temperatures for die casting. Aggregate variable values are used for the cost modelling developed in this study and then used d to estimate the costs per manufactured unit. Data used in the following sections was obtained from Boothroyd et al, (2003), DoE (1999) and Kalpakjian and Schmid (2006).

The capital recovery life of the main machine, L_M, is the time (in years) over which the capital investment is recovered by distributing it over the components being produced. In order to prevent the burden of capital recovery to be concentrated in one component, the capital recovery rate can be the same as the expected physical life of the machine.

Similarly, the capital recovery life of the tool, L_{CT}, is the logarithm of the number of the production cycles (L_{Tn}) over which the capital investment on tools is recovered by distributing its costs over the component being produced. For the SSM process, the tools are mould or/and die tools. The recovery life of the tool can be defined as (Busch, 1983):

$$L_{CT} = \log L_{Tn} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(4)$$

Another process variable is the variable that is used to determine the total costs of the auxiliary equipment per main machine (e.g. conveyors, air-compressors, etc) that is necessary for the successful implementation of the manufacturing process (excludes auxiliary automation equipment such as robotics, forklifts, external PLCs, etc.). This variable is represented by R_{Aux} and determines the fraction of the total costs for all the auxiliary

equipment to the total cost of the main machine costs. It can be represented by the following equation:

$$R_{Aux} = \frac{C_{Aux}}{C_{M.M.}} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(5)$$

The variable that is used to determine the total installation costs per main machine reflects the total costs of installing the main machine, setting-up the building (e.g. plumbing, electrical, etc.) and installation of auxiliary equipment. It is represented by R_{Inst} and it is determines the fraction of the total installation costs to the total costs of the main machine i.e.,

$$R_{Inst} = \frac{C_{Inst}}{C_{M.M.}} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(6)$$

In the work presented in this study, C_{Inst} was calculated using data from literature for forging and die casting and from direct cost information for SSM.

The variable that is used to determine the total overhead costs per main machine reflects the total cost incurred due to quality control, cleaning costs, managerial costs, etc. The overhead cost is represented by R_{Over} and it determines the fraction of the total overhead costs per main machine to the total cost of the manufacturing a component.

$$R_{Over} = \frac{C_{Ovr}}{C_{T.C.}} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(7)$$

The variable that is used to determine the total maintenance costs per main machine incorporates maintenance costs for the following; main equipment, auxiliary equipment, required labour and any capital costs (excludes any tooling related costs). It is represented by R_{Maint} and it determines the fraction of the total maintenance costs that comprise the total costs of main machine.

$$R_{Maint} = \frac{C_{Maint}}{C_{M.M.}} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(8)$$

Quantification of the parameters R_{Inst}, R_{Over} and R_{Maint} as ratios of total main machine costs and total costs simplifies their determination. Experienced engineers or plant operators can readily quantify these parameters in the form presented above.

The variable that is used to determine the total direct labour requirements indicates the number of hourly paid labourers required to operate the main machine and other direct labour required during the manufacturing process. It is represented by $n_{D.L.}$ The data obtained from literature for both forging and die casting combined the costs of operating main machine machines and auxiliary machines with the costs of operators for these machines. The data was used as available as it does not affect the final cost analysis. In order to separate machine operating cost and the cost of its operator, the cost model developed in the spreadsheet software assumed a certain hourly pay rate for operators. Operators' hourly pay rate can be

changed by the user of the cost model i.e. it is an input variable. The data that was used for SSM was direct data from an expert.

Productivity of the manufacturing process determines the efficiency of the manufacturing process to produce quality components i.e. stability of the manufacturing process. It is represented by e_P and determined as the ratio of the total productive hours per main machine (only when acceptable quality components are being manufactured) to the total available machine hours on the main machine. It was assumed that implementing best practice of quality standards and continuous improvement (which are a prerequisite in a modern competitive environment), that all the manufacturing processes would achieve the same level of efficiency. As such, this was not included as a parameter that varies from one manufacturing processes to the other.

The scrap rate of a manufacturing process has been described in the previous section, and it is represented by S. It represents all the non-recyclable material lost during trimming and material of those components that do not meet the design specifications. S can be defined by the following mathematical expression:

$$S = \frac{w_s}{w} \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \quad (9)$$

where w = the total weight of the final component in kilograms,
  w_s is the total weight of scrap material produced per final component, after subsequent manufacturing processes such as trimming and machining.

For forging, scrap rate is caused by flashes, scale and scrap. For die casting, material loss is caused by sprues, runners, biscuits etc. S was determined by calculating the volume of the final component, and the volume of the scrap material for all the three processes. Additional 2% scrap rate was added in casting for loss of molten material during pouring, and for forging for loss due to scale. For SSM, 0.5% of additional material loss was added due to scale.

The variable that is used to determine the total costs of utilities consumption per main machine reflects the amount of costs incurred by heating, cooling, transporting material, etc, during processing. It is represented by C_E and it specifies the average cost of energy consumed per kilogram of processes material. It does not include the energy used by main and auxiliary machines. The energy used by main and auxiliary machines is included in the operating cost for running these machines. Different methods were used to determine energy requirements for heating as widely different amounts of energy are required for melting the metal for casting, and for warming the metal for hot forging. Much more energy is required for melting the metal.

Operational and Financial Variables

Operational and financial variables affect the cost of production directly but have no inherent statistical error caused by limitations of the model methodology (Busch, 1983). Operational variables are:
- Wages of direct labourers in rand[1], including employee benefits ($W_{D.L.}$),
- Number of working days per calendar year (n_d),
- Number of shifts per working day (n_s), and
- Number of hours worked per shift (n_{hrs}).

Financial variables are:
- Price of utilities in rand per KWh (P_{Ut}),
- Price of factory floor space in rand per m^2 ($P_{F.S.}$),
- Capital recovery life/depreciation life of buildings in years (L_{Bld}),
- Capital recovery rate on investments in percentage form (R), and
- Price of raw material in rand per kg ($P_{R.M.}$).

The price of raw materials can be obtained from the London Metal Exchange (LME) for estimation.

Adjustment Factors

Adjustment factors increase or decrease certain parameters by a certain amount due to material being processed and the geometry of the part being produced. The following material adjustment factors were inherent in the data that was used:
- Adjustment to utilities consumption ($Adj_{Mat.Ut.}$)
- Adjustment to life of tools ($Adj_{Mat.L.T.}$)
- Adjustment to scrap rate ($Adj_{Mat.S.}$)
- Adjustment to cycle time ($Adj_{Mat.C.}$)
- Adjustment to cost of tools ($Adj_{Mat.C.T.}$)

The following material adjustment factors were not inherent in the data which was used and they were not accounted for due to lack of data:
- Adjustment to cost of auxiliary equipment ($Adj_{Mat.C.Aux.}$)
- Adjustment to cost of main machine ($Adj_{Mat.C.M.M.}$)
- Adjustment to life of main machine ($Adj_{Mat.L.M.M.}$)

The following are four geometry adjustment factors were inherent in the data used and/or were calculated:
- Adjustment to cost of tools ($Adj_{Geo.C.T.}$)
- Adjustment to scrap rate ($Adj_{Geo.S.}$)
- Adjustment to cycle time ($Adj_{Geo.C.}$)

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[1] At the time of writing the exchange rate was 1 US dollar ($1-00) = 7 SA rand (R7-00)

- Adjustment to life of tools ($Adj_{Goe.L.T.}$)

Regression Factors

Regression variables are those variables that are required to complete the cost model. They are used to calculate machine, tool and building costs. Their use is further elaborated in the sections below.

Variable Costs

a) Material cost per finished component, C_{Matr}

$$C_{Matr} = \left(\frac{w * P_{Matr}}{1 - S} \right) \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \quad (10)$$

where P_{Matr} = price of raw material costs per kilogram, and

S = the scrap rate - a measure of the amount of raw material which does not become incorporated in the final product, including that which is trimmed as offal (i.e. wasted material) and that which is lost due to the production of parts which do not meet the design specifications (i.e. amount of process stability).

b) Utilities cost per component, C_{Ut}

Cost of utilities is adjusted for material, as materials need differing latent energy of heating during the melting process. This is only applicable to those processes where material must be heated or cooled using external energy. It also includes the cost of energy for moving components. Cost of utilities can be described by the following equation:

$$C_{Ut} = w * \overline{E} * C_E * Adj_{MatL.Ut.} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \quad (11)$$

where C_{Ut} is the total cost of utilities that are consumed during the manufacturing of one component,

$\overline{E}$ is the average energy (heating, cooling, mechanical transport, etc.) consumed per kilogram of the material that is processed, and

C_E is the cost of energy per kilogram of the manufactured component in R/KWh. It must be adjusted for other energy costs that are not electrical.

Material adjustment factors for utilities are not used in the spreadsheet model as they were not found in open literature. They are recommended for use by a manufacturer from in-house experience in process improvement studies.

c) Direct labour cost per component, $C_{D.L.}$

$$C_{D.L.} = \frac{T_C * W_{D.L.} * n_L}{e_p} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \quad (12)$$

where $C_{D.L.}$ is the total cost of direct labour per finished component, including benefits,

T_C is the average cycle time for manufacturing a component,

$W_{D.L.}$ is the wage rate in rand per hour of direct labour,

n_L is the number of labourers required per machine for manufacturing of one component, and

e_P is the productivity or efficiency of the manufacturing process.

The direct labour costs are based on the cycle times required to produce the components. The data that was found in literature combined direct labour costs with costs for running main and auxiliary machines. Information on direct labour costs used to aggregate the cost was not available; therefore it was not feasible to develop a model that can separate the two. The data was used as found and direct labour costs were not adjusted.

d)   Cycle time for cyclic processes, T_C

The cycle time is adjusted for both material and geometry of the component. Some materials have good heat conduction properties, thus reducing the solidification in casting. Some geometries have thick sections which takes some time to solidify during casting.

$$\log(T_C) = \left(C1\log w + C2\right) * Adj_{Mat.C.} * Adj_{Geo.C.} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (13)$$

where $C1$ and $C2$ are regression variables of the graph of log (cycle time) v/s log (weight) under different processing conditions (Busch, 1983).

The cycle times that were used in this study were determined from empirical data and they were adjusted for material effects only. This allowed only the use of the left-hand side of Equation 13 to be used in this work. Moreover, regression variables C1 and C2 were not found in literature, so it was hard to use the right-hand side of equation 13.

Fixed Costs

a)   Machine costs, $C_{M.M.}$

Machine costs are adjusted for material that is used to manufacture the components. Some materials are corrosive or abrasive and machines must be special designed to handle such materials (Busch, 1983).

$$C_{M.M.} = \frac{n_m e^{(M1\log w + M2)} Adj_{Matr.C.M.M.}}{L_M} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..\ldots\ldots\ldots.(14)$$

where n_m is the total number of main machines in the production line operating in parallel,

$M1$ and $M2$ are regression coefficients obtained from the graph of log (main machine price) to log (w), and

L_M is machine life that is based on the amortisation life of equipment and it is expressed as amortisation life of machine in years (or M_{La}) which is adjusted for the

material that is being processed on the machine (e.g. hard metals reduce the lifespan of machines) i.e.

$$L_M = M_{La} * Adj_{Mat.L.M.M.} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots..(15)$$

In this work, the costs of main machines used were found in literature, and graphs were used to determine the costs of the main machines. Equation 14 was used in a slightly different form.

b) Number of machines operating in parallel, n_m

$$n_m = \frac{n * T_c}{e_p * n_d * n_s * n_{hrs}} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(16)$$

where n is the number of manufactured components required in a year. In this study, it is assumed that only one main machine is used (Busch, 1983).

c) Tool costs, C_T

The cost of tools is adjusted for the complexity of the component to be manufactured. Complex shapes might require additional inserts and additional machining when they are manufactured. The tool costs are described by the following equation:

$$C_T = \frac{n_m e^{(T1 \log w + T2)} Adj_{Geo.C.T.}}{L_T} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots..(17)$$

where $T1$ and $T2$ are regression variables of graph of log (price of tool) v/s log (weight),
L_T is the life of tool in number of production cycles (Busch, 1983).

d) Tool life, L_T

Tool life is adjusted for both material and geometry of the component to be manufactured. Abrasive materials and complex components can shorten the life span of the mould. The tool life can be estimated by the following equation:

$$L_T = \frac{e^{\log L_{Tn}} * Adj_{Matr.L.T.} * Adj_{Geo.L.T.}}{n} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots.\dots(18)$$

where L_{Tn} is the expected life of the mould in cycles (Busch, 1983). In this study, tool life was assumed to be 40 000 for both SSM and hot forging.

e) Installation costs of main machine, C_{Inst}

$$C_{Inst} = C_{M.M} * R_{Inst} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots..(19)$$

f) Maintenance cost of main machine, C_{Maint}

$$C_{Maint} = C_{M.M} * R_{Maint} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots..(20)$$

g) Building costs or factory floor space costs, C_{Bld}

$$C_{Bld} = \frac{A * P_{F.S.}}{L_{Bld}} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots.(21)$$

where A is the total area occupied by the equipment required for manufacturing products,
$P_{F.S.}$ describes the price of factory floor space in rand per square meters (price of building/square meters),
L_{DepBld} is the depreciation life of building in years using the straight-line method (Busch, 1983).

h) The total floor space required to manufacture and warehouse the component, A

$$A = e^{(Bld1*\log w + Bld2)}(1 + 0.3(n_m - 1))\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(22)$$

where $Bld1$ and $Bld2$ are regression variables for the graph log (floor space costs) v/s log weight (Busch, 1983).

This equation was not implemented in the developed model as regression variables for building were not found in literature for the different manufacturing processes. Equation 22 takes into consideration the space required for raw materials, work-in-process, and finished components.

i) Auxiliary equipment costs, C_{Aux}

$$C_{Aux} = C_{M.M} * R_{Aux} * Adj_{Mat.C.Aux.} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots..(23)$$

where $Adj_{Mat.C.Aux}$ is used when material require special handling or pre-conditioning prior to processing (Busch, 1983).

Material adjustment factors for auxiliary equipment were not implemented in the model as they were not found in literature for the chosen materials.

j) Overhead costs, C_{Ovr}

$$C_{Ovr} = C_{T.C.} * R_{Ovr} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots.(24)$$

k) Capital recovery costs, C_R

$$C_R = \frac{C(-1 + (1\_R)e^L)\log(1+R)}{(1+R)e^{L-1}} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (25)$$

where R = capital recovery rate or internal rate of return,
L, or Life = recovery life of investment
C, or capital costs is defined as the total combined costs of main machine, tools, building, auxiliary equipment and 3 months' working capital (alternatively it can be made 3 months of expenditures on variable costs and overheads).

This equation is a continuous interest capital recovery equation. It has been modified such that payback of investment principal is subtracted from the capital recovery. Capital costs are

estimated for the main machine, tools, building and auxiliary equipment. (Busch, 1983) In this work, Equation 25 is used in a simplified form. A straight line depreciation method is used.

Results

Analysis of total manufacturing costs for the three manufacturing processes presented in this section is conducted using Component 1 depicted in Figure 1. The quantity of components to be manufactured is 150 000. Figure 5 below compares total estimated manufacturing costs for die-casting, CSIR's SSM and hot forging. Hot forging costs are the highest, while SSM costs are the lowest for the conditions and assumptions made in the cost estimation model. The difference in total manufacturing costs between hot forging and CSIR's SSM is R750 000 ($107,000) .
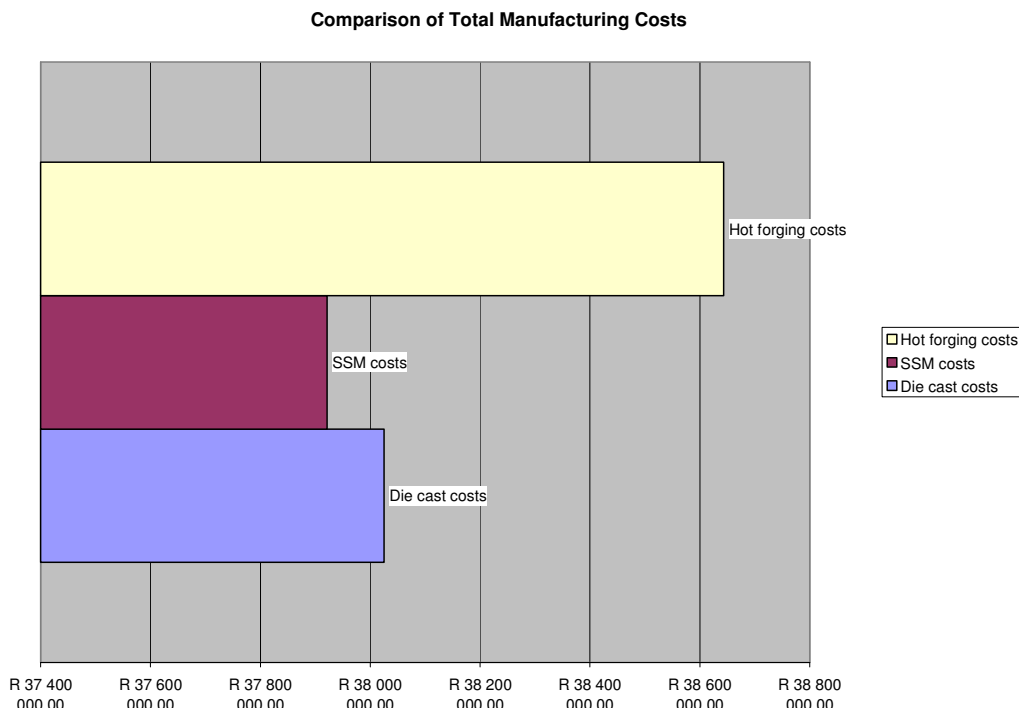

Figure 5. Comparison of total manufacturing costs for different manufacturing processes.

Figure 6 below shows total manufacturing costs per component of die casting, CSIR's SSM and hot forging as the total number of components manufactured is changed from 50 0000 to 10 million. Manufacturing costs per component is reduced from around R395 ($56) to around R190 ($27) for hot forging and from around R370 ($53) to around R198 ($28) for SSM, and from around R330 ($47) to around R185 ($26) for die casting.

Other analyses that were conducted were:

- Analysis of total manufacturing costs for each manufacturing process
- Effect of material choice on manufacturing costs
- Effect of component complexity on manufacturing costs
- Sensitivity of manufacturing costs to different parameters

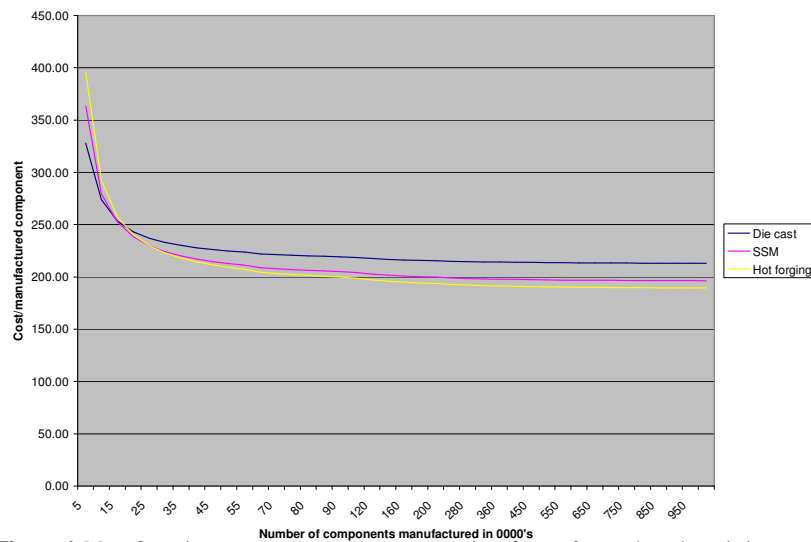The results are discussed in the next section and are nor presented here due to space constraints.

Figure 6. Manufacturing costs per component as quantity of manufactured products is increased.

Discussion and Conclusion

Between 150 000 and 260 000 units CSIR's SSM total manufacturing costs are lower than that of die casting and hot forging. Outside this range, SSM cost is lower than hot forging cost but higher than die casting cost up to a number of components less than 150 000. For more than 260 000 components CSIR's SSM total manufacturing cost is lower than die casting costs but higher than hot forging costs.

Choice of material greatly affects the total costs of manufacturing as material costs amount to approximately 70% of the total manufacturing costs, and about 90% of variable manufacturing costs. It is important to choose a material that is relatively inexpensive compared to metals in its class, but that can satisfy specifications of the component. This can be achieved through material substitution. CSIR SSM process has been designed for use with aluminium which is lightweight and is comparatively cheaper than other non-ferrous metals. Other techniques that can be used to reduce manufacturing costs that are related to material are:

- Use of material substitution,

- Redesign a component so that it has less curved surfaces and reduced surface area in order to reduce its complexity (use DFM philosophy), and
- Optimisation of CSIR SSM manufacturing process for reducing the runner and sprue system.

Sensitivity analysis has revealed that the different kind of costs that have considerable effect on the total manufacturing costs are; material costs, main machine costs, auxiliary equipment costs, and overhead costs. From this, it can be determined that the engineering parameters that have considerable effect on the total manufacturing costs are; price of raw materials for component, product complexity, prices of manufacturing equipment and auxiliary equipment and efficiency of the overall manufacturing enterprise.

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