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Fuzzy logic cost estimation method for high production volume components

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**FUZZY LOGIC COST ESTIMATION METHOD FOR
HIGH PRODUCTION VOLUME COMPONENTS**

By

Shirley J. Copen

A THESIS

Submitted to

The College of Engineering and Mineral Resources

at

West Virginia University

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For the degree of

Master of Engineering

in

Industrial Engineering

ABSTRACT

FUZZY LOGIC COST ESTIMATION METHOD FOR HIGH PRODUCTION VOLUME COMPONENTS

By Shirley J. Copen

The purpose of this research is to develop fuzzy logic cost models that estimate the cost of a component based on the component's geometric shape, size, material and manufacturing process. The research is focused on components made from high production quantity processes i.e. stamping, injection molding, rolling and extrusion. However, the method may also be used for other types of manufacturing processes. The method is useful to both engineers and cost estimators whenever an estimated cost is desired. Engineers and cost estimators may use the method to obtain the cost of components or products of similar design without a detailed estimate. The objective is to develop a cost estimation method that is easy and simple to use.

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1.0 Literature Review

1.1 Material Selection Methods

The selection of materials for a component is not an easy process because there are approximately 50,000 to 60,000 materials available for design. Since there are so many material available some type of method is required to select materials. Dieter [1] states that a material selection method requires four steps. The first step is to identify the material requirements for the component. The material selected must function in the environment and at the service conditions required for the component. The second step is to screen candidate materials by comparing the material requirements of the component and the properties of the material. This comparison eliminates those materials that do not have suitable properties. The third step is to select candidate materials by comparing the performance, the cost, the manufacturing process and availability of each material. The fourth step is to test the selected materials. Materials are tested in a simulated environment to determine whether the material functions properly for the given service conditions. Dieter describes six methods of material selection that use the four steps described above: the cost-performance method, the weighted material property method, the value analysis method, the failure analysis method, the benefit-cost analysis method and the expert system method.

The cost-performance method uses the relative cost per unit material property for various design service conditions. The two properties used are the strength of the material and

the stiffness of the material. The cost performance ratio for strength is a function of the material density (ρ), the material cost (C_m) and the strength of the material (σ). The cost-performance ratio for strength (C_σ) in simple is equal to $C_m \rho / \sigma$. The cost performance ratio for stiffness is a function of the material density (ρ), the material cost (C_m) and the modulus of elasticity of the material (E). The cost-performance ratio for stiffness (C_E) in simple tension is equal to $C_m \rho / E$. To use the cost-performance method both cost-performance ratios must be satisfied. This is accomplished by determining the maximum area at the point where the load is applied. For example, if a component is in simple tension the strength is equal to the load (P) divided by the area (A) or $\sigma = P/A$. The deflection (δ) is equal to the load (P) multiplied by the length of the component (L) divided by area (A) multiplied by the modulus of elasticity (E). The area for the cost-performance strength ratio is $A = P / \sigma$. The area for the cost-performance stiffness ratio is $A = PL/E\delta$. Thus, the area used $A_{\text{used}} = \text{Max} [p / \sigma, PL / E\delta.]$ Since the maximum area is used both the strength of the component and the stiffness of the component meet the performance conditions. The cost-performance method is limited because it may only be used when one constraint is applied.

To illustrate the application of the cost-performance method consider the material selection of rods for a material-handling device. The application requires that the rods hold a distributed load of 0.25 lbs/in. The rods must be 72 inches long and must not deflect more than 1 inch. The rods must be round. There are two types of rod materials available, steel and Teflon. The first step in applying the cost-performance method is to determine the maximum area required for both materials given the required service

conditions. The area for the cost-performance strength ratio is $A = P^{3/2} / \sigma_b$. P is the load on the rod and σ_b is the bending stress. The area for the cost-performance stiffness ratio is $A = Pl / E^{1/2} \delta$. P is the load on the rod and l is the length of the rod. E is the modulus of elasticity of the material and δ is the deflection. The load on the rod is 0.25 lbs /in * 72 inches = 18 lbs. The bending strength of steel is 36,000 lbs/in² and the bending strength of Teflon is 4000 lbs/in². The modulus of elasticity of steel is 30 x 10⁶ lbs/in² and the modulus of elasticity of the Teflon is 95,000. The maximum area required for the steel is:

$$A_{\text{steel}} = \text{Max} [P^{3/2} / \sigma_b, Pl / E^{1/2} \delta]$$

$$A_{\text{steel}} = \text{Max} [(18^{3/2} / 36,000), ((18 * 72) / ((30 \times 10^6)^{1/2} * 1.0))]$$

$$A_{\text{steel}} = \text{Max} [0.00212 \text{ in}^2, 0.23662 \text{ in}^2]$$

$$A_{\text{steel}} = 0.23662 \text{ in}^2$$

The maximum area required for Teflon is:

$$A_{\text{Teflon}} = \text{Max} [P^{3/2} / \sigma_b, Pl / E^{1/2} \delta]$$

$$A_{\text{Teflon}} = \text{Max} [(18^{3/2} / 4,000), ((18 * 72) / ((95,000)^{1/2} * 1.0))]$$

$$A_{\text{Teflon}} = \text{Max} [0.01909 \text{ in}^2, 4.20478 \text{ in}^2]$$

$$A_{\text{Teflon}} = 4.20478 \text{ in}^2$$

For both materials, the area for the stiffness is the maximum area. The rod diameter required for the Teflon is:

$$\text{Diameter} = ((4 * A_{\text{Teflon}}) / \pi)^{1/2}$$

$$\text{Diameter} = ((4 * 4.20478 \text{ in}^2) / \pi)^{1/2}$$

$$\text{Diameter} = 2.314 \text{ inches}$$

The rod diameter required for the steel is:

$$\text{Diameter} = ((4 * A_{\text{steel}}) / \pi)^{1/2}$$

$$\text{Diameter} = ((4 * 0.23662 \text{ in}^2) / \pi)^{1/2}$$

$$\text{Diameter} = 0.54888 \text{ inches}$$

The Teflon rod is available in a 2.375-inch diameter. The cost of the Teflon rod is \$6.00 per inch. The Teflon rod required for this application would cost \$6.00 * 72 inches = \$432.00 per rod. The steel rod is available in a 0.625-inch diameter. The cost of the steel rod is \$4.67 per inch. The steel rod required for this application would cost \$4.67 * 72 inches = \$336.00 per rod. Thus, the cost-performance method indicates the steel is the cheapest material for the application.

The weighted material property method assigns weights to material properties in order of importance to the design. The most important material property has a value of 100. Material properties without values are either go or no-go. In other words, a material is either resistant to corrosion or it is not, weld able or it is not, available in a given shape or it is not. Combinations that are a function of the most important property are generated

once the assignment of values to all the important properties is complete. The weighed factor for each property is a function of the number of times the property selection occurs. The material selection comes about by multiplying each property by the weighed factor and summing the values. The material with the highest total is selected. The weighted material property method takes material selection one step further in that this method takes into account all of the design factors including factors without actual values such as weld ability, corrosion resistance and shape.

To illustrate the application of the weighted material property method, consider the example used for the cost-performance method. However, this time additional material properties are considered. The first consideration is the parts must slide on the rods without sticking. This means the material must have a low friction coefficient. This is the most important property because the primary function of the material handling device is to slide parts from station to station. Parts must slide along the rods with minimum friction. In addition, the rods must not be too heavy because the rods are located at the top of the material-handling device. The second consideration is that the rods are located at the top of the material-handling device. This means the material must be lightweight. Thus, the properties to be considered in the selection of the rod material are the stiffness, the bending strength, the density and the friction coefficient. To apply the weighted material property method, the first step is to assign a weight to each material property. The weight assigned depends on the importance of the property to the required service conditions. For this application, the most important property is the friction coefficient. The second most important property is the weight (density) of the rods. The material

handling device must not upset or create a safety hazard. The third most important property is the stiffness. The rods must not bend as the load slides between the stations. The fourth most important property is the bending strength. Weights may be assigned to the properties in different ways. However, one of the best ways to assign weights is to use a digital logic table. In a digital logic table each property is listed and compared to every other property two at a time. The property that is considered more important is given a 1 and the other property is given a 0. The total number of combinations is $N = n(n-1) / 2$, where n is the number of properties being evaluated. The digital logic table is shown in Table 1-1. The digital table gives the friction coefficient a weight of 3 or 30 %, the density a weight of 2 or 20% and the stiffness a weight of 1 or 10%. The bending strength is not weighted.

The next step is to apply the weight factors to the materials, Teflon and steel, and determine the material performance index. Table 1-2 below shows the comparison. The materials are assigned values based on which one has the lowest or highest of the given property. Teflon has the lowest friction coefficient and since a low friction coefficient is desired Teflon is assigned a 30. Teflon has the lowest weight. Thus, Teflon is assigned a 20 in the density column. Steel has the highest stiffness as shown in the previous example. Steel is assigned a 10 in the stiffness column. Steel also has the highest bending strength. However, as stated above the bending strength is not weighted. Adding up the weights gives steel a material performance index of 10 and Teflon a material performance index of 50. Thus, Teflon is the selected material.

Table 1-1 Digital Logic Table

PROPERTIES	FRICTION COEFFICIENT	DENSITY	STIFFNESS	BENDING STRENGTH	TOTAL
Friction Coefficient		1	1	1	3
Density	0		1	1	2
Stiffness	0	0		1	1
Bending Strength	0	0	0		0

Table 1-2 Material Performance Index

MATERIAL	FRICTION COEFFICIENT	DENSITY	STIFFNESS	BENDING STRENGTH	MATERIAL PERFORM INDEX
STEEL			10	0	10
TEFLON	30	20			50

The value analysis method of material selection is a disciplined method of analysis. This method can benefit both new and existing component designs. The first step in using the method is to collect information about the function and cost of the design. Once the information is gathered, a team is formed from various technical disciplines. The team examines the design in detail and determines whether each design function is a necessity. If the function is necessary, the team decides whether there should be a manufacturing process change or a material change made to the design. The changes made to the design depend on the functional requirements and the cost. For example, a product system currently consists of two products. Product 1 is made from steel and several

subcomponents. The main structure of Product 1 is made in a large progressive die. Product 2 is also made from steel but is rolled and cutoff in a rolling mill. Due to the size of Product 1, the main structure must be purchased from an outside vendor because the company does not have a large enough press. Product 1 is assembled on a large production line by thirteen operators. Product 2 is made in-house. However, Product 2 also requires an assembly line with three operators. A value analysis is performed on the product system. The first item that is analyzed is the process. How can the main structure of Product 1 be changed so that the Product may be made in-house? Proposals are made and a decision is reached that a better process may be to injection mold the main structure. An in-house injection molder is available to make the main structure. Analysis shows that plastic could be used to replace the main structure. The team then looks at Product 2. Is there a better way to make Product 2? Again, proposals are made and a decision is reached that the structure of Product 2 could also be made in the in-house injection molder. Finally, the team reaches the conclusion that not only can the products both be made from plastic, but the products can also be attached and made at the same time in the injection molder. Now, only one assembly line is required. The value analysis reduced the cost of both products and reduced the labor required to make the product system.

The failure analysis method is a method used on new products. The first step in using the method is to select a multifunctional team. This team looks at the product from different viewpoints. The team usually consists of design engineers, product engineers, manufacturing engineers, industrial engineers and quality engineers. The method

involves evaluating as many failure modes as possible for the design. Collection of historical data used in the development of similar products provides a basis for analysis. From this data, the engineers develop categories for all possible failure modes. The engineers then calculate the probability of the failure occurring. To counteract failures that have a high probability of occurrence, the engineers develop procedures to prevent the failure, change the manufacturing process or change the materials used in the product. For example, a team is assembled to develop a new product for an existing product line. Failures that have occurred before include: spring failures, missing clips, and miss-assembled cables. The team evaluates each failure. For the spring failure, the team determines that the spring ends need to be redesigned and that a stronger material is needed for the spring. For the missing clip failures, the product is designed so that the clips are no longer required. For the miss-assembled cable failure, the cables are color-coded and the ends of the cables are redesigned so that the cables only fit in the product in the desired orientation.

The benefit-cost analysis method of material selection starts with a reference design. This method ranks material alternatives with respect to cost. The lowest-cost material is the initial reference. The lowest-cost material is compared with the next highest cost material by determining the incremental benefit and cost. If the ratio of the incremental benefit to the incremental cost is less than one the lowest cost material is selected and compared to the next material. If it is not less than one the second lowest cost material is chosen and compared to the next material. This evaluation continues until the benefit-

cost ratio is greater than one. The first material that produces a cost-benefit ratio greater than one is selected.

The expert system method of material selection is performed with knowledge bases that contain data on materials. Usually the expert systems are industry specific. The data within the expert system is obtained from experts in a field who are knowledgeable about the process and the materials used in the process. Most expert systems go through a series of questions that ask the user to enter a response about a given product application. The expert system may ask questions about the size of the product, the process used to fabricate the product or the environment the product will operate in. The information requested by the expert system corresponds to a series of “IF.... THEN” rules. The rules are used by an inference engine that logically deduces which materials should be selected for the application or product.

Another type of material selection method has been developed by Ashby [2]; the Ashby method of material selection divides materials into six primary classes: metals, ceramics, glasses, plastics, elastomers and composites. Metals are subdivided into aluminum alloys, copper alloys, lead alloys, magnesium alloys, molybdenum alloys, nickel alloys, steels, tin alloys, titanium alloys, tungsten alloys and zinc alloys. Ceramics are subdivided into alumina, diamond, sialons, silicon carbide, silicon nitride and zirconia. Glasses are subdivided into borosilicate, soda and silica. Plastics are subdivided into epoxies, melamines, polycarbonates, polyesters, polyethylene, high-density polyethylene, polyformaldehyde, polymethylmethacrylate, polypropylene, polytetrafluorethylene and

polyvinylchloride. Elastomers are subdivided into natural rubber, hard butyl rubber, polyurethanes, silicone rubber and soft butyl rubber. Composites are subdivided into carbon fiber reinforced polymer, glass fiber and Kevlar fiber.

Ashby has developed material property charts to determine the materials that may be selected for a particular design. The Ashby method uses relationships between properties or attributes to determine which group of materials may be used for a design. These relationships maximize the performance of the component. For example, in the density-modulus of elasticity chart the relationship for axial loading of a beam is E/ρ where E is the modulus of elasticity and ρ is the density. The relationship for buckling of a slender column is $E^{1/2}/\rho$ and the relationship for the bending of a plate is $E^{1/3}/\rho$. The relationships are represented as a line on the chart. Materials that lay on the line perform equally well in that particular design application. Materials that lie above the line perform better in the design application and materials that lie below the line do not perform as well as those on the line or above the line.

The density-strength chart plots the density of a material against the strength of the material. The strength plotted is the yield strength for metals and polymers, the crushing strength for ceramics, the tear strength for elastomers and the tensile strength for composites. The performance ratios for this chart are $\sigma/\rho = C$, where σ is the strength, ρ is the density, and C is a constant for axial loading of a beam. For a slender column, the performance ratio is $\sigma^{2/3}/\rho = C$, where σ is the strength, ρ is the density, and C is a

constant for buckling of a column. For a plate, the performance ratio is $\sigma^{1/3} / \rho = C$ where σ is the strength, ρ is the density, and C is a constant for bending of a plate.

The fracture toughness-density chart plots the density of a material against the fracture toughness of the material. The crack resistance of a material is fracture toughness. The performance ratio for this chart is $K_{IC} / \rho = C$ where K_{IC} is the fracture toughness, ρ is the density and C is a constant. These three charts are used to select materials for designs that require minimum weight.

The modulus of elasticity-strength chart plots the modulus of elasticity against the strength. The performance ratio for this chart is $\sigma / E = C$ where σ is the strength as defined above, E is the modulus of elasticity and C is a constant. The specific stiffness-strength chart plots the ratio of the modulus of elasticity to density against the ratio of the strength to density for each material. The performance ratio for this chart is $\sigma / \rho E = C$. These two charts are used to select materials for designs that require both minimum component size and strength.

The fracture toughness-strength chart plots the fracture toughness of a material against the strength of the material. This chart is used to select materials for pressure vessel designs where “link before break” or “yield before break” is important. The performance ratio for this chart is K_{IC}^2 / σ_f , where K_{IC} is the fracture toughness and σ_f is the yield strength.

The loss coefficient-modulus of elasticity chart plots the loss coefficient of a material against the modulus of elasticity. The performance ratio for this chart is $\eta = C / E$ where C is a constant, E is the modulus of elasticity and η is the loss coefficient. The loss coefficient is either the ability of the material to vibrate or the material's ability to dampen vibration.

The thermal conductivity-diffusivity chart plots the thermal conductivity of a material against the thermal diffusivity. Thermal conductivity is the flow of heat through a material at steady state. Thermal diffusivity is the flow of heat through a material over time. The performance ratio for this chart is $\lambda / a = C$, where C is function of the density of the material and the specific heat of the material, λ is the thermal conductivity of the material and a is the thermal diffusivity of the material.

The thermal conductivity-thermal expansion chart plots the linear expansion coefficient of a material against the materials thermal conductivity. The linear expansion coefficient of a material measures the displacement or expansion of a material as it is heated. The performance ratio for this chart is $\lambda / \varepsilon = C$ where C is a constant value, λ is the thermal conductivity and ε is the linear expansion coefficient.

The thermal expansion-modulus of elasticity chart plots ε the linear expansion coefficient of a material against the modulus of elasticity E . The performance ratio for this chart is $\varepsilon = C / E$. C is a constant; E is the modulus of elasticity and ε is the linear expansion coefficient.

The thermal expansion-normalized strength chart plots the linear expansion coefficient of a material against the normalized strength. The normalized strength is different depending on the material. For metals and polymers, the normalized strength is the tensile yield strength divided by the modulus of elasticity (E) of the material. For ceramics, the normalized strength is the tensile fracture strength divided by the modulus of elasticity (E) of the material. For composites, the normalized strength is the stress that causes the fibers to debond divided by the modulus of elasticity (E) of the material. The performance ratio for the chart is $C = \Delta T / (1 + \alpha E)$ where ΔT is the temperature change, B is a function of $(\epsilon + 1) * \epsilon * E$ and ϵ is the coefficient of expansion.

The modulus of elasticity-relative cost chart plots the modulus of elasticity of a material against its relative cost. The cost of the material per kilogram divided by the cost per kilogram of mild steel rod is the relative cost. The performance ratio for a beam is $C = E / C_R \rho$ where E is the modulus of elasticity, C_R is the relative cost and ρ is the material density. The performance ratio for a column is $C = E^{1/2} / C_R \rho$. The performance ratio for a plate is $C = E^{1/3} / C_R \rho$.

The strength-relative cost chart plots the modulus of elasticity of a material against its relative cost. The cost of the material per kilogram divided by the cost per kilogram of mild steel rod is relative cost. The performance ratio for a beam is $C = \sigma / C_R \rho$ where σ is the strength, C_R is the relative cost and ρ is the material density. The performance ratio for a column is $C = \sigma^{1/2} / C_R \rho$. The performance ratio for a plate is $C = \sigma^{1/3} / C_R \rho$.

Ashby has taken the charts described above and developed a PC based software package called the Cambridge Material Selector (CMS) which allows the user to select materials for a design. The package consists of 167 engineering materials and provides detailed information about each material's properties or attributes. To use the package the user selects the range for each material property desired. Material selections may be made on several charts depending on the design. The CMS then screens the database for any materials that meet the given criteria and prints materials that meet the criteria in another window. The user can decrease the list by applying additional constraints until one material is selected. The user can develop any performance ratio desired from the available material properties. The limitation of this software package is that it only allows the user to select materials. Process selection is not considered. A new package, the Engineering Materials Selector considers processes that can be used by the material, but cannot readily optimize material and process selection.

1.2 Process Selection Methods

The selection of manufacturing processes at the initial stage of a design is important because the right decision at this point in the design process saves on the overall cost of the design and makes the design easier to manufacture. It also lowers the cost of the equipment and tooling required to manufacture the design.

The Ashby [2] method of manufacturing process selection is similar to the Ashby material selection method. The Ashby method of process selection gives manufacturing

processes attributes that describe what the process does. The attributes include: the material used in the process, the complexity of the design, the dimension tolerance of the design, the surface finish required on the design, the and the cost of the manufacturing process. Ashby arranges these attributes into process selection charts similar to the material selection charts used in the material selection method. There are five types of process selection charts: the size-shape chart, the size-complexity chart, the size-melting point chart, the hardness-melting point chart and the surface finish-tolerance chart.

The size-shape chart plots the minimum section thickness. The component size is along a diagonal line with a negative slope. The component size increases as the surface area and minimum section thickness increase. The slenderness ratio is also along a diagonal line, however it has a positive slope. The slenderness ratio decreases as the surface area and minimum section thickness decrease. The sphere forms the shape limit for a component because it is not possible to create shapes with a smaller surface to component size ratio. The slenderness ratio defines the shape. Together the component size and the slenderness ratio form the boundaries for the fabrication process. Thus, the size and shape of the component limits the process selected for fabrication.

The complexity-size chart plots the complexity of the component against the size or weight of the component. To define complexity this chart uses three factors: the number of independent dimensions of the component, the tolerance range on the component dimensions and the symmetry of the component. The number of dimensions is different depending on the shape desired. A sphere has one dimension the radius, a cylinder has

two dimensions, the radius and the length, and a tube has three dimensions the radius, the length and the wall thickness. The complexity of the component increases as the number of dimensions increase. The complexity also increases as the tolerance range on each dimension decreases. The complexity of the component increases as the component becomes less symmetric.

To calculate the complexity used in the chart, Ashby uses the following equation:

$$C = n \log_2[l / \Delta l] \quad [1-1]$$

Where C is the complexity:

l is equal to the geometric mean dimension, $[l_1 * l_2 * l_3 \dots l_n]^{1/n}$

Δl is equal to the geometric mean precision, $[\Delta l_1 * \Delta l_2 * \Delta l_3 \dots \Delta l_n]^{1/n}$

n is the number of component dimensions.

The size-melting point chart plots the melting point of various materials against the size or weight of the component. The size of the component is plotted on the vertical axis. The processes are blocked on the chart. The block shows the minimum and maximum temperatures and minimum and maximum sizes for the process.

The hardness-melting point chart plots the hardness of the material selected against the melting point of the material selected. The processes are blocked on the chart. The block

shows the minimum and maximum hardness and the minimum and maximum melting points for the process.

The tolerance and surface finish chart plots the surface roughness against the tolerance range for each process. Relative cost factors are plotted diagonally on the chart showing the relative cost of each process to other processes. Cost increases as the tolerance range decreases and the surface roughness decreases.

The Ashby and Ewasi [3] method of fabrication process selection classifies processes into process classes. There are five process classes: primary, secondary, tertiary, joining and finishing. Primary fabrication processes take unshaped material and give the material shape. Examples are extrusion, casting, molding, stamping and machining. Secondary fabrication processes modify, add or refine features to a component that has been shaped. Thus, some processes belong to both the primary and secondary process classes e.g. machining processes. Tertiary processes add mass to the component or surface to the component e.g. shot peening. Joining processes add size to the component. Welding, brazing and soldering are examples of joining processes. Finishing processes change the surface of the component. Honing, lapping, buffing and sand blasting are examples of finishing processes.

Like the Ashby method, the Ashby and Ewasi method links the fabrication processes to materials, shapes, surface roughness, tolerance, section thickness and cost. The difference is that the Ashby and Ewasi method defines classes for materials and shapes.

The method makes the surface roughness, tolerance, section thickness, cost, adjacent section ratio, the hole diameter, the minimum corner radius, the maximum dimension, the quality factor, the batch size, the capital cost, the tooling cost, the lead time, the material utilization, the production rate and the tool life process attributes.

The Ashby and Ewasi method links the fabrication process to five general material classes: metals, ceramics, naturals, polymers and composites. Each general material class is subdivided. Metals are subdivided into ferrous, non-ferrous, light alloy, reactive and refractory. Ceramics are subdivided into fine, glasses, hydrated and vitreous. Naturals are subdivided into stone and wood. Polymers are subdivided into thermoplastics, thermo sets, elastomers and foams. Composites are subdivided into metal-matrix, ceramic-matrix, thermoplastic-matrix and the thermo set-matrix. A process may be linked to one or more materials.

There are three shape classes: prismatic, sheet and 3-D. Each shape class is subdivided. The prismatic shape class is subdivided into axisymmetric or non-axisymmetric. Both axisymmetric and non-axisymmetric shapes may be solid with or without a step or hollow with or without a step. The sheet shape class is subdivided into flat with and without cutouts and dished which is further subdivided into axisymmetric shallow, deep reentrant and deep non-reentrant and non-axisymmetric shallow, deep reentrant and deep non-reentrant. The 3-D shape class is subdivided into solid and hollow. The 3-D solid class and the 3-D hollow class are both subdivided into parallel and transverse with re-entrants and no-reentrants.

Ashby and Ewasi have developed a software package that uses charts to represent the method. This method is similar to the CMS developed by Ashby. The Ashby and Ewasi method allows an engineer to select or screen for processes by plotting a process class against an economic or physical attribute. It also allows an engineer to select or screen for processes by plotting a material class or shape class against an economic or physical attribute. The number of screenings required depends on the design requirements. Various case studies are presented for different types of designs. All case studies have a process class, a shape class and a material class selected for the design. Material attributes and economic attributes vary according to the design requirements.

1.3 Cost Estimation Methods

Various cost estimation methods have been developed to estimate the cost of new components. The parametric cost estimating method uses component parameters or features to estimate costs. The parameters or features generally used are the size, the shape and the material. This cost estimation method has been used since the 1950's. Creese [4] discusses parametric cost equations developed by Boeing in 1961 and modified by Zenger [7]. The equations estimate the processing costs for sand, permanent mold, die and investment castings. The cost equations are a function of the quantity of material per casting and the number of parts produced. The equations are:

$$\text{Cost}_{\text{sand}} = 8.2 \times V^{0.72} + 1030 \times V^{0.51} / N$$

$$\text{Cost}_{\text{permanent mold}} = 0.3 + 2 \times V^{0.7} + (517 + 101 \times V) / N$$

$$\text{Cost}_{\text{die}} = 0.56 + 0.3 \times V + 3660 \times V^{0.27} / N$$

$$\text{Cost}_{\text{investment}} = 15.3 \times V^{0.57} + 1700 \times V^{0.3} / N$$

Where, V = Casting Volume, cubic inches

N = Number of parts produced

Another type of parametric cost estimation method uses cost functions. This method takes parameters from a known design and ratios the parameters to obtain the cost of the new design. The only restriction is that a component or product has similar parameters that drive the cost of the design. Information is derived from known costs for these parameters or cost drivers. Cost functions have been developed for turned and milled parts turned parts, welding, rolling mills, fixtures, and gears and molded components Wierda [5]. There are also equations for forging Creese [6].

Other types of parametric methods have been developed by Ashby [2] as discussed in Section 1.2. The complexity-size chart uses the dimensions of a component to determine the component complexity. Complexity increase with dimension size, the tightness of the tolerance and the number of dimensions it takes to define a component. The tolerance-surface finish chart defines a relative cost factor for a process that is a function of the surface roughness and the tolerance range. This has also been discussed by Creese [4,6].

The tables developed by Ashby are partially based on a material / process cost estimation method developed by Zenger [7] in 1989. The primary focus of the Zenger method was to estimate the tooling cost for fabricating a part. The tooling cost of a component changes with the production quantity. If the production quantity is low then the tooling cost per piece will be high. In other words, if only a few parts are to be produced the tooling cost will drive the cost of the design. If the production quantity is high then the tooling cost per piece will be low. The material and process cost will drive the cost of the design.

The Zenger cost-estimating method calculates the cost of a component based on the geometry of the component and the production quantity required. Zenger used a new cost estimation technique for sheet metal working. To estimate the tooling cost for sheet metal working Zenger developed equations to calculate manufacturing base points for various types of sheet metal dies. The manufacturing base points are a function of the component size and the complexity of the component. The Zenger method defines the component size as the surface area of the component i.e. the length of the component times the width of the component. Complexity (CPX) is defined to be the periphery (P) of the component squared divided by the surface area (A) of the part.

$$CPX = P^2 / A \quad [1-2]$$

For example, the complexity of a rectangular component that is 2 inches wide and 3 inches long would be:

$$CPX = (2 + 3 + 2 + 3)^2 / (2 * 3) = 100 / 6 = 16.67$$

The production quantity is introduced by using a production quantity correction factor.

The correction factor is:

$$VC = [UTS_m / UTS_{ms}] * V * T_m^2 * 0.02 \quad [1-3]$$

Where,

UTS_m = ultimate tensile strength of the material

UTS_{ms} = ultimate tensile strength of mild steel

V = production quantity

T_m = the thickness of the part

The manufacturing base points calculated from the equations are multiplied by the production quantity correction factor to obtain manufacturing cost per hour. The manufacturing cost per hour is then multiplied by the average burdened labor rate to obtain the cost of the die.

For comparison purposes, Zenger used the equations developed by Boeing in 1961 to estimate the process and tooling cost of various types of castings. For injection molding, Zenger modified a cost estimating technique developed by Archer and Dewhurst [8]. The Archer and Dewhurst method calculates the cost of an injection mold. This method is similar to the manufacturing point method for estimating the cost of dies. Zenger added a geometric complexity factor and a tolerance level factor to the method.

For machining, Zenger modified methods developed by Boothroyd [9] and Radovanovic [10]. The Radovanovic method divided machining into seven categories; primary rotational, primary rotational with secondary, primary planar, primary planar with secondary, primary rotational and primary planar, primary rotational and primary planar with secondary and secondary. Radovanovic developed equations for each of these seven categories. However, the equations require that an engineer know the number of machining operations required, the number of machines required, the number of clampings required, the average drill diameter and average mill cutter diameter. Zenger simplified the method by using complexity factors. A complexity factor of one is simple and a complexity factor of five or more is complex. Zenger used the complexity factor to define the number of machine operations required, the number of machines required and the number of clampings. To define the drill diameter and the mill cutter diameter Zenger used a length of component ratio.

Zenger compared the processes and the materials by estimating the cost of two components made from various processes and materials. In all cases, the component size was the cost driver if the production quantity was small and the material was the cost driver if the production quantity was large.

1.4 Fuzzy Logic Cost Models

Fuzzy logic is based on fuzzy set theory which was introduced by Lotfi Zadeh [11] in 1965. In the beginning it was not accepted. However, Lotfi Zadeh persisted and

continued to demonstrate its effectiveness until in the 1970s E. H. Mandami started using fuzzy logic in industrial applications. Since that time, fuzzy logic has been developed into a useful and powerful tool. Today, fuzzy logic is used in industrial applications, business applications, health care applications and hybrid fuzzy logic/neural network applications.

The use of fuzzy logic to determine cost was recently proposed in a paper written by Mason and Levy [12]. The paper's focus was to determine the cost of ceramic blanks using a fuzzy logic expert system. The cost drivers used in the expert system were the ceramic blank size and complexity. The size and the complexity were used as the premises in the expert system rules.

Expert systems use rules to capture knowledge about a given subject. The rule is written in an "if ...then" format. Each rule is composed of a "IF" premise clause and a "THEN" conclusion clause. In a fuzzy logic expert system, the premises and conclusions are both stated linguistically. Each premise and each conclusion are associated with a fuzzy set. In the case of the ceramic blank, size was represented as "very small", "small", "moderately small", "medium", "moderately large", "large" and "very large". The complexity of machining was represented as "low", "medium" and "high". The cost was represented as "very low cost", "low cost", "moderate low cost", "moderate cost", "moderate high cost", "high cost" and "very high cost". The number of rules used in the expert system was $3 \times 7 = 21$. The relationship of the premises to the conclusions is shown in Table 1-3.

The fuzzy expert system developed by Mason and Levy uses the min-max inference method to determine the cost. The min-max inference method compares the premises and selects the premise with the minimum membership. For example, suppose the rule is “If the complexity is low (membership 0.8) and the size is very large (membership 0.6) the cost is moderate.” The membership of the cost in the moderate cost set is 0.6, which is the minimum of the two premises. Once the membership in the cost fuzzy set is determined, the min-max inference method compares the memberships of the conclusions and selects the maximum membership. For example, suppose another rule states: “If the complexity is medium (membership 0.7) and the size is medium (membership 0.5) the cost is moderate.” The membership of the cost in the moderate set is 0.5, which is the minimum of the two premises. Both rules give memberships for the moderate cost set. However, the membership used for the moderate cost set is 0.6, which is the maximum of the two conclusions.

Mason and Levy demonstrate how the fuzzy logic cost model is used for crisp inputs. Crisp inputs are actual values for the size and complexity of the ceramic blank. For two crisp inputs, Mason and Levy assume that the size of the ceramic blank is 550 in³ and the complexity of the ceramic blank is 3 on a scale of 1 to 10. The volume is considered a very large volume. The complexity is considered low. The very large volume has a membership of 0.84 in the very large volume complexity set. The complexity has a membership of 0.67 in the low complexity set. The rule is “If the volume of the ceramic blank is very large (0.84) and the complexity of the ceramic blank is low (0.67) then the

Table 1-3 Relationship of Premises to Conclusions

	Very Small Volume	Small Volume	Moderately Small Volume	Medium Volume	Moderately Large Volume	Large Volume	Very Large Volume
High Complexity	Moderately High Cost	Moderately High Cost	Moderately High Cost	High Cost	Very High Cost	Very High Cost	Very High Cost
Medium Complexity	Very Low Cost	Very Low Cost	Moderate Cost	Moderate Cost	Moderately High Cost	Moderately High Cost	Moderately High Cost
Low Complexity	Very Low Cost	Very Low Cost	Low Cost	Low Cost	Moderately Low Cost	Moderate Cost	Moderate Cost

cost is moderate.” Thus, the membership of the cost in the moderate cost set would be 0.67. For this particular example, the moderate cost set is the only cost set considered. Figure 1-1 shows the cost function for the moderate set. The shape of the cost function is trapezoidal. The centroid of the cost function is located at \$1000. This is the defuzzified cost value.

Figure 1-1 Moderate Cost Set for Crisp Example

2.0 Model Fundamentals

2.1 Methodology

A fuzzy logic cost model is developed by using various equations for the component size, complexity and cost of a component. The size is defined as the volume of the component in cubic inches. The parts are weighed and the volume is calculated by multiplying the weight by the density. The density is either 0.283 in³ for steel, 0.041in³ for plastic or 0.098 in³ for aluminum.

The complexity is a function of the geometric shape of the part, the processes used to fabricate the component and the material used. The total complexity is

$$C_{\text{Total}} = C_{\text{Shape}} * C_{\text{P}} * (C_{\text{S1}} * C_{\text{S2}} * \dots * C_{\text{SN}}) * C_{\text{material}}$$

Where, C_{Shape} = geometric shape complexity

C_{P} = complexity contributed by the primary forming processes

$C_{\text{S1}}, C_{\text{S2}}, C_{\text{SN}}$ = complexities contributed by the finishing processes

C_{Material} = complexity contributed by the material

The shape complexity is obtained from Ashby's equation discussed in Section 1.2.

$$C_{\text{Shape}} = n \log_2 (L / \Delta L)$$

$$\text{Where, } L = (L_1 * L_2 * L_3 * \dots * L_N)^{1/N}$$

$$\Delta L = (\Delta L_1 * \Delta L_2 * \Delta L_3 * \dots * \Delta L_N)^{1/N}$$

The equation, $L = (L_1 * L_2 * L_3 * \dots * L_N)^{1/N}$ reduces all the geometric dimensions of the component to a mean dimension. The equation, $\Delta L = (\Delta L_1 * \Delta L_2 * \Delta L_3 * \dots * \Delta L_N)^{1/N}$ reduces all the geometric dimension tolerances of the component to a mean dimension tolerance. For example, the component shown in Figure 2-1 has nine dimensions. The component is 4 inches by 3 inches by 2 inch by 1 inch by 7/16 inch. The component is 3/16 inch thick. A hole is located 1/2 inches from the side and 1 7/8 inches from the end. The hole is 1/2 inch in diameter. The mean dimension is:

$$L = (L_1 * L_2 * L_3 * L_4 * L_5 * L_6 * L_7 * L_8 * L_9)^{1/9}$$

$$L = (4 * 3 * 2 * 1 * 7/16 * 1/2 * 3/16 * 1/2 * 1 7/8)^{1/9}$$

$$L = 0.918 \text{ inch}$$

The tolerance is 0.0 inches to 1/16 inch for the 4-inch, the 3-inch and the 2-inch dimensions. The tolerance is 0.0 inches to 1/32-inch for the 1 7/8-inch, 1-inch, the 7/16-inch, the 3/16-inch, 3/16-inch and 1/2 -inch dimensions. The mean dimension tolerance is:

$$\Delta L = (\Delta L_1 * \Delta L_2 * \Delta L_3 * \Delta L_4 * \Delta L_5 * \Delta L_6 * \Delta L_7 * \Delta L_8 * \Delta L_9)^{1/9}$$

$$\Delta L = (1/16 * 1/16 * 1/16 * 1/16 * 1/32 * 1/32 * 1/32 * 1/32 * 1/32)^{1/9}$$

$$\Delta L = 0.043 \text{ inch}$$

The primary process complexity contribution is a function of the component size, the complexity of the process and the cost of the process. If the size of the component is small and the complexity of the process is simple, the cost of the process is low. Thus, the small parts have a primary complexity contribution of 1.0. The primary complexity contribution becomes greater than 1.0 as the size of the component or the complexity of the process increases. This increase is captured by dividing the process cost of the small, simple part, SS, into the process cost of the large, complex part, LC. Thus, the primary complexity contribution is $C_{\text{primary}} = LC / SS$.

Figure 2-1 Example Part

Secondary process complexity contributions are a function of the complexity of the secondary processes required to finish the part, the cost of the process and the primary processes used to form the part. The secondary complexity contribution is 1.0 if the primary process molds or forms the component into its final finished shape. In other words, no secondary processes are required to finish the part. The secondary complexity contribution becomes greater than 1.0 if the primary process does not form the component to its final finished shape or additional processes are required to strengthen or protect the part. This increase is captured by dividing the primary process cost, PPC, into the secondary process cost, SPC and adding the result to 1.0. The result is added to 1.0 because the secondary costs are in addition to the primary cost and 1.0 is the secondary complexity contribution if the primary process molds or forms the component into its final finished shape. Thus, a secondary complexity contribution is

$$C_{\text{secondary}} = \text{SPC} / \text{PPC} + 1.0.$$

The material complexity contribution is a function of the cost of the process. The material complexity contribution is 1.0 if only one material is used in a particular process. However, if additional materials are used the material complexity contribution decreases for the lower cost materials. The decrease is captured by dividing the smaller cost material, SMC, by the largest cost material, LMC. The material complexity of the highest cost material remains 1.0. Thus, the equation for the material complexity is $C_{\text{material}} = \text{SMC} / \text{LMC}$. For example, Material A costs \$1.00 / lb, Material B costs \$0.75 / lb and Material C costs \$0.90 / lb. The material complexity of Material A is equal to 1.0,

the material complexity of Material B is equal to 0.75 and the material complexity of Material C is equal to 0.90.

The cost of a component is a function of the material, process and tooling cost. The largest contributor to the cost is the type of material. The second largest contributor is the cost of the primary or forming fabrication process. Secondary or finishing process costs are usually small in comparison to the primary process cost but do contribute to the overall cost. Tooling cost as discussed in Section 1.3 is an important cost contributor if the number of parts produced is small. However, if the number of parts produced is large the contribution of tooling to the overall cost is very small. The total cost used for this model is

$$\text{Cost}_{\text{Total}} = \text{Cost}_{\text{Material}} + \text{Cost}_{\text{Primary}} + \sum \text{Cost}_{\text{Secondary}}$$

2.2 Model Flow Chart

The flow chart in Figure 2.2-1 shows the equations used to develop the component sizes, complexities and costs for the fuzzy logic cost model. These equations are the equations required to develop the input data for a particular model.

Figure 2-2 Model Flow Chart

3.0 Fuzzy Logic Cost Estimation Method

3.1 Methodology

The fuzzy logic cost estimation method uses parametric cost estimation, fuzzy logic expert system methodology and fuzzy logic set theory to estimate the cost of making a component from a raw material. Parametric cost estimation is a cost estimating method that uses design parameters such as the size, the weight or the complexity to determine a component's cost. These parameters are also called cost drivers because the parameters drive or determine most of a component's cost. The design parameters used in this fuzzy logic cost estimation method are the size and the complexity.

The size of a component determines both the amount of material and the size of the equipment required to make the component. The complexity of a component determines the type of materials and processes used to make the component. Thus, the complexity of a component is actually a function of the geometric shape, the material selected and the process selected. The geometric shape determines the number of dimensions and tolerances required to make the product. Ashby's equation is used to calculate the shape complexity.

$$C = n \log_2 [l / \Delta l]$$

Where C is the complexity

l is equal to the geometric mean dimension, $[l_1 * l_2 * l_3 \dots l_n]^{1/n}$

Δl is equal to the geometric mean precision, $[\Delta l_1 * \Delta l_2 * \Delta l_3 \dots \Delta l_n]^{1/n}$

n is the number of component dimensions

The shape complexity increases as the number of dimensions increase and the tolerance range on each dimension decreases. For example, Component 1 is a rectangular object with a length of 10 inches, a width of 2 inches and a thickness of 0.5 inches. The tolerance on the 10-inch length is 0.00 to 1/8 of an inch, the tolerance on the 2-inch width is 0.0 to 1/16 of an inch and the tolerance on the 0.5-inch thickness is 0.0 to 1/32 of an inch. The shape complexity of Component 1 is calculated as follows:

Number of component dimensions, $n = 3$

Geometric mean dimension, $l = [l_1 * l_2 * l_3]^{1/3}$

Geometric mean dimension, $l = [10 * 2 * 0.5]^{1/3}$

Geometric mean dimension, $l = 2.154$ inches

Geometric mean precision, $\Delta l = [\Delta l_1 * \Delta l_2 * \Delta l_3]^{1/3}$

Geometric mean precision, $\Delta l = [1/8 * 1/16 * 1/32]^{1/3}$

Geometric mean precision, $\Delta l = 1/16$ inch or 0.0625 inches

Complexity, $C = n \log_2[l / \Delta l]$

Complexity, $C = 3 * \log_2[2.154 / 0.0625]$

Complexity, $C = 15.32$

The complexity of Component 1 is 15.32. Component 2 is like Component 1 except that it has a hole in the middle. The hole has a diameter of $\frac{1}{4}$ of an inch with a tolerance of $\frac{1}{32}$ of an inch. The shape complexity of Component 2 is:

Number of component dimensions, $n = 4$

Geometric mean dimension, $\bar{l} = [l_1 * l_2 * l_3 * l_4]^{1/4}$

Geometric mean dimension, $\bar{l} = [10 * 2 * 0.5 * 0.25]^{1/4}$

Geometric mean dimension, $\bar{l} = 1.257$ inches

Geometric mean precision, $\Delta l = [\Delta l_1 * \Delta l_2 * \Delta l_3 * \Delta l_4]^{1/4}$

Geometric mean precision, $\Delta l = [1/8 * 1/16 * 1/32 * 1/32]^{1/4}$

Geometric mean precision, $\Delta l = 0.0525$ inches

Complexity, $C = n \log_2[\bar{l} / \Delta l]$

Complexity, $C = 4 * \log_2[1.257 / 0.0525]$

Complexity, $C = 18.33$

The shape complexity of Component 2 is higher than Component 1 because there is an additional dimension and tolerance.

Material selection is a function of the complexity because the material selected directly affects the process used to make the product. The material selected may slow the process down or create additional scrap. The material selected may add to the cost of the equipment required for the process or increase the labor cost associated with the process. Labor cost may be affected by the amount of maintenance required to keep the equipment running or the amount of labor required to run the process. Process selection is a function of the complexity because the process selected determines the cost of the equipment, the tooling, the processing rate and the cost of the labor required to maintain and run the equipment.

Fuzzy logic expert systems use rules to relate input sets called premises and output sets called conclusions. The rules are the logic and are written in "if...then" format. In this application, the size and the complexity are the input sets and the costs are the output set. For example, if the size is low and the complexity is low then cost is low.

Fuzzy set theory is used to determine the membership of each size, the complexity and cost in the input and output sets. The basic concept is that membership in a fuzzy set is a value between 0.0 and 1.0. A 1.0 means the size, complexity or cost is a full member of the set. A 0.0 means the size, complexity or cost is not a member of the set. A value between 0.0 and 1.0 indicates the relative amount of membership a size, complexity or cost has in the set. To define this state between full membership in the fuzzy set and no membership in the fuzzy set linguistic variables are used. The linguistic variables "low", "medium" and "high" describe the various levels between 0.0 and 1.0.

Fuzzy expert systems use inference procedures to determine the amount of membership in the output set. The most common inference procedure used is the min-max procedure. The min-max inference procedure selects the minimum membership value for the premises in the rule. For example, suppose the size is small and the complexity is low but the membership of the component in the size set is 0.5 and the membership of the complexity in the complexity set is 0.4. The min-max inference procedure selects the complexity membership because between the two premises this is the minimum membership. The min-max inference procedure selects the maximum membership for the conclusions. For example, suppose there are three rules that give the conclusion that the cost is low. One rule gives a membership of 0.4, one rule gives a membership of 0.3 and one rule gives a membership of 0.6. The min-max inference procedure selects the maximum membership of 0.6 as the cost membership.

3.2 Development

The first step in applying the fuzzy logic cost method is to develop a database of components with known sizes, complexities and costs. For this research databases were developed for a stamped component set, two injection molded component sets, a rolled component set and an extruded component set. The sizes, complexities and costs for each set of components are converted into fuzzy sets. To simplify, three fuzzy sets are modeled for the size, complexity and cost. The sets are defined as low, medium and high.

Membership in the low size, low complexity or low cost fuzzy sets is calculated by dividing the smallest size, complexity or cost by all the other sizes, complexities or costs. To normalize, the smallest size, complexity or cost is set to zero and all other memberships are reduced by the amount required. For example, if the volume of the smallest component is 0.65 in^3 and the volume of the largest component is 8.5 in^3 . The membership of the largest component in the low size fuzzy set is $0.076 [0.65 \text{ in}^3 / 8.5 \text{ in}^3]$. Since the membership of the largest component is not zero, 0.076 is subtracted from the largest component membership and all other component size memberships. Thus, the largest component has a membership of 0.0 in the small component size set.

Membership in the high size, high complexity or high cost fuzzy sets is calculated by dividing the largest actual component size, highest complexity or highest cost into all the other component sizes, complexities or costs in the set. Again, once all the memberships are calculated for the largest component size, highest complexity or highest cost fuzzy sets, the sets are normalized. For example, if the smallest component size is 0.65 in^3 and the largest component size is 8.5 in^3 , then the membership of the smallest component size in the high size fuzzy set is $0.076 [0.65 \text{ in}^3 / 8.5 \text{ in}^3]$. Since the membership of the smallest component size is not zero, 0.076 is subtracted from the smallest size membership and all other component memberships. Thus, the smallest component has a membership of $0.0 \{ [0.65 \text{ in}^3 / 8.5 \text{ in}^3] - 0.076 \}$ in the high size fuzzy set.

Membership in the medium size, medium complexity or medium cost set is calculated by subtracting the memberships of the low and high fuzzy sets from 1.0. The memberships

are subtracted from 1.0 because the total membership of a volume, complexity or cost in all sets is always equal to 1.0. For example, if a component has a membership of 0.3 in the low size set and a membership of 0.5 in the high size set, then the component will have a membership of 0.2 in the medium size set $[1.0 - 0.3 - 0.5]$.

The fuzzy sets for volume and complexity are related to the fuzzy cost sets as shown in Table 3-1.

Table 3-1 Relationship of Fuzzy Sets

	Small	Medium	Large
High Complexity	Medium Cost	High Cost	High Cost
Medium Complexity	Low Cost	Medium Cost	High Cost
Low Complexity	Low Cost	Low Cost	Medium Cost

There are three volume premises and three complexity premises. Thus, there are 9 $[3*3]$ rules. The rules are defined as:

Rule 1: If complexity is low and the size is low then the cost is low.

Rule 2: If complexity is low and size is medium then the cost is low.

Rule 3: If complexity is low and size is high then the cost is medium.

- Rule 4: If complexity is medium and the size is low then the cost is low.
- Rule 5: If complexity is medium and the size is medium then the cost is medium
- Rule 6: If complexity is medium and the size is high then the cost is high.
- Rule 7: If complexity is high and the size is low then the cost is medium.
- Rule 8: If complexity is high and the size is medium the cost is high.
- Rule 9: If complexity is high and the size is high then the cost is high.

3.2.1 Stamped Components

The stamped component set consists of ten components. Table 3-2 gives the volume for each component. The volumes are in cubic inches (in^3). To develop the fuzzy sets, the minimum volume is set to 0.0 in^3 . The maximum volume is set ten percent higher than the largest component volume.

To calculate the small fuzzy set memberships, the smallest component size, 0.121 in^3 , is divided by each of the other component sizes. The membership of the smallest component size is 1.0. The membership of the largest component size is 0.125. Table 3-3 shows the initial memberships for each component.

Table 3-2 Volumes of the Stamped Component Set

Component	Volume
Minimum	0.000 in ³
1	0.121 in ³
2	0.136 in ³
3	0.189 in ³
4	0.316 in ³
5	0.349 in ³
6	0.375 in ³
7	0.398 in ³
8	0.596 in ³
9	0.784 in ³
10	0.883 in ³
Maximum	0.971 in ³

Note the largest part, 0.971 in³, does not have a membership equal to 0.0. This means, the fuzzy set needs to be normalized such that the largest component size has a membership of 0.0 in the small fuzzy set. The set is normalized by subtracting 0.125 from all the initial memberships except for 0.0, which remains 1.0. Table 3-4 gives the normalized memberships for each component.

To calculate the large fuzzy set memberships, the largest component size, 0.971 in³, is divided into each of the other component sizes. The membership of the largest component is 1.0. The membership of the smallest component is 0.125. Table 3-5 gives

the initial memberships for each component.

**Table 3-3 Initial Memberships of the Small Fuzzy Set
(Stamped Components)**

	Minimum 0.000 in ³	1.000
1	0.121 in ³	1.000
2	0.136 in ³	0.890
3	0.189 in ³	0.640
4	0.316 in ³	0.383
5	0.349 in ³	0.347
6	0.375 in ³	0.323
7	0.398 in ³	0.304
8	0.596 in ³	0.203
9	0.784 in ³	0.154
10	0.883 in ³	0.137
Maximum	0.971 in ³	0.125

Note the smallest component size, 0.121 in³, does not have a membership equal to 0.0. This means, the fuzzy set needs to be normalized such that the smallest component size has a membership of 0.0 in the large fuzzy set. The fuzzy set is normalized by subtracting 0.125 from all the initial memberships. Table 3-6 gives the normalized memberships for each component.

Table 3-4 Normalized Memberships of the Small Fuzzy Set

(Stamped Components)

Component	Volume	Membership
Minimum	0.000 in ³	1.000
1	0.121 in ³	0.875
2	0.136 in ³	0.765
3	0.189 in ³	0.515
4	0.316 in ³	0.258
5	0.349 in ³	0.222
6	0.375 in ³	0.198
7	0.398 in ³	0.179
8	0.596 in ³	0.078
9	0.784 in ³	0.029
10	0.883 in ³	0.012
Maximum	0.972 in ³	0.000

To calculate the medium fuzzy set memberships, the membership of the component in the small fuzzy set and the membership of the component in the large fuzzy set are subtracted from 1.0. Table 3-7 gives the memberships for each component in the medium fuzzy set.

The complexity is a function of the geometric shape, the primary process and secondary processes used to make the component. A primary process is the process that forms the general shape. Stamping is the primary process. A secondary process is defined as a process that adds strength, continues to change the shape or adds material to a component. Deburring, tumbling, heat-treating, plating and injection molding are secondary processes for the stamped component set.

Table 3-5 Initial Memberships of the Large Fuzzy Set
(Stamped Components)

Component	Volume	Membership
Minimum	0.000	0.000
1	0.121	0.125
2	0.136	0.140
3	0.189	0.195
4	0.316	0.325
5	0.349	0.359
6	0.375	0.386
7	0.398	0.410
8	0.596	0.614
9	0.784	0.807
10	0.883	0.909
Maximum	0.972	1.000

Ashby's equation is used to calculate the shape complexity.

$$C = N \log_2 [L / (\Delta L)]$$

Where,

C is the complexity

L is the geometric mean dimension, $[l_1 * l_2 * l_3 \dots l_n]^{1/N}$

ΔL is the geometric mean precision or tolerance on each dimension, which is

defined as $[\Delta L_1 * \Delta L_2 * \Delta L_3 \dots \Delta L_N]^{1/N}$

N is the number of dimensions

Table 3-6 Normalized Memberships of the Large Fuzzy Set**(Stamped Components)**

Component	Volume	Membership
Minimum	0.000	0.000
1	0.121	0.000
2	0.136	0.015
3	0.189	0.069
4	0.316	0.200
5	0.349	0.234
6	0.375	0.261
7	0.398	0.285
8	0.596	0.488
9	0.784	0.682
10	0.883	0.784
Maximum	0.972	0.875

Table 3-7 Component Memberships in the Medium Fuzzy Set**(Stamped Components)**

Component	Volume	Membership
Minimum	0.000	0.000
1	0.121	0.125
2	0.136	0.220
3	0.189	0.415
4	0.316	0.542
5	0.349	0.544
6	0.375	0.541
7	0.398	0.536
8	0.596	0.434
9	0.784	0.289
10	0.883	0.204
Maximum	0.971	0.125

An EXCEL spreadsheet simplifies the calculations. Table 3-8 shows the spreadsheet for the stamped component set. The first column under each component contains the geometric dimensions and the second column contains the tolerance on each dimension. The number of dimensions or tolerances in the column is labeled N and is located at the top of the column. The geometric mean dimension is located directly below the geometric dimensions and is labeled L. The geometric mean precision is located directly below the geometric tolerances and is labeled ΔL . The shape complexity is located at the bottom of the first column and is labeled C. To verify that the spreadsheet calculates the correct shape complexity the calculations for Component 1 are shown below.

Number of component dimensions, $n = 3$

Geometric mean dimension, $L = [l_1 * l_2 * l_3]^{1/3}$

Geometric mean dimension, $L = [1.375 * 0.75 * 0.188]^{1/3}$

Geometric mean dimension, $L = 0.579$ inches

Geometric mean precision, $\Delta L = [\Delta l_1 * \Delta l_2 * \Delta l_3]^{1/3}$

Geometric mean precision, $\Delta L = [1/16 * 1/16 * 1/32]^{1/3}$

Geometric mean precision, $\Delta L = 0.050$ inches

Complexity, $C = n \log_2 [L / \Delta L]$

Complexity, $C = 3 * \log_2 [0.579 / 0.050]$

Complexity, $C = 3 * \log_2 [11.667]$

Complexity, $C = 3 * 3.544$

Complexity, $C = 10.632$

The primary process complexities are calculated from known process costs. The stamped components are made with either a progressive or a fein blank die. The stamped components are made in high production volumes. As noted by Zenger [7], equipment cost is minimal when components are made in high production volumes. Thus, the primary process cost is the labor required to run the press. The cost per piece for a progressive die is \$0.00872 per piece. The cost per piece for a fein blank die is \$0.00374 per piece. The difference in labor cost is due to the speed of the press and the number of components made at one time. From Figure 2-1 the primary complexity is equal to cost of a progressive die component divided by the cost of a fein blank die component.

$$C_{\text{primary}} = LC / SS$$

$$C_{\text{primary}} = \$0.00872 / \$0.00374$$

$$C_{\text{primary}} = 2.33.$$

Thus, for the stamped component set, components made with a progressive die have a primary process complexity of 2.33. Components made with a fein blank die have a primary process complexity of 1.00.

The secondary process complexities are also calculated from known process costs. The secondary processes for the stamped component set vary with the component. E-coat is a

secondary process for components made with a progressive die. Plating is a secondary process for components made with a fein blank die. Heat-treat is a secondary process for components made with a fein blank die. Deburr is a secondary process for components made with a fein blank die. Tumbling is a secondary process for components made with a fein blank die. Barrel plating is a secondary process for components made with either a fein blank die or a progressive die. Injection molding is a secondary process for components made with a fein blank die. Again, equipment costs are minimal because the components are made in high production volumes. Thus, the secondary process cost is the labor required to e-coat, plate, heat-treat, deburr, tumble, barrel plate or injection mold a component. Table 3-9 shows the costs for both the primary and secondary processes.

The secondary process complexities are calculated by finding the relative cost of the secondary process to the primary process. Secondary process complexities are calculated by adding the ratio of the secondary process cost and primary process cost to one. Table 3-10 shows the secondary process complexities for the stamped component set.

Table 3-8 Shaped Complexities for Stamped Components

Component 1		Component 2		Component 3		Component 4		Component 5	
4.00	4.00	3.00	3.00	3.00	3.00	3.00	3.00	4.00	4.00
0.77	0.03	0.78	0.06	1.25	0.06	1.75	0.06	2.06	0.06
0.20	0.03	0.25	0.03	0.75	0.06	0.50	0.03	0.91	0.06
0.16	0.03	0.06	0.03	0.19	0.03	0.09	0.03	0.25	0.03
0.06	0.03							0.19	0.03
0.20	0.03	0.23	0.04	0.56	0.05	0.43	0.04	0.54	0.04
10.64		7.64		10.51		10.39		14.49	
Component 6		Component 7		Component 8		Component 9		Component 10	
3.00	3.00	4.00	4.00	15.00	15.00	20.00	20.00	14.00	14.00
5.81	0.06	1.31	0.06	4.44	0.06	4.63	0.06	4.88	0.06
1.25	0.06	0.81	0.06	1.88	0.06	1.88	0.06	1.88	0.06
0.19	0.03	0.69	0.06	1.50	0.06	1.00	0.06	1.75	0.06
		0.19	0.03	1.31	0.06	1.00	0.06	1.50	0.06
				1.31	0.06	1.00	0.06	1.31	0.06
				1.06	0.06	0.81	0.06	1.00	0.06
				0.81	0.06	0.81	0.06	0.94	0.06
				0.75	0.06	0.56	0.03	0.69	0.06
				0.44	0.03	0.56	0.03	0.38	0.03
				0.44	0.03	0.56	0.03	0.31	0.03
				0.31	0.03	0.56	0.03	0.25	0.03
				0.25	0.03	0.44	0.03	0.19	0.03
				0.25	0.03	0.38	0.03		
						0.38	0.03		
						0.31	0.03		
						0.25	0.03		
						0.25	0.03		

Table 3-9 Process Costs for Stamped Components

Primary Process	Cost	Secondary Process	Cost
Progressive Die	\$0.00872 per piece	E-Coat	\$0.00138 per piece
Fein Blank Die	\$0.00374 per piece	Plating	\$0.00138 per piece
Fein Blank Die	\$0.00374 per piece	Heat -Treat	\$0.00034 per piece
Fein Blank Die	\$0.00374 per piece	Deburr	\$0.00067 per piece
Fein Blank Die	\$0.00374 per piece	Tumbling	\$0.00043 per piece
Progressive Die	\$0.00872 per piece	Barrel Plating	\$0.00748 per piece
Fein Blank Die	\$0.00374 per piece	Barrel Plating	\$0.00748 per piece
Fein Blank Die	\$0.00374 per piece	Injection Molding	\$0.02615 per piece

Table 3-10 Secondary Process Complexities**(Stamped Components)**

Secondary Process	Primary Process	1 + Ratio	Secondary Process Complexity
E-Coat	Progressive Die	1 + \$0.00138 / \$0.00872	1.16
Plating	Fein Blank Die	1 + \$0.00138 / \$0.00374	1.37
Heat -Treat	Fein Blank Die	1 + \$0.00034 / \$0.00374	1.09
Deburr	Fein Blank Die	1 + \$0.00067 / \$0.00374	1.18
Tumbling	Fein Blank Die	1 + \$0.00043 / \$0.00374	1.11
Barrel Plating	Fein Blank Die	1 + \$0.00748 / \$0.00374	3.00
Barrel Plating	Progressive Die	1 + \$0.00748 / \$0.00872	1.86
Injection Molding	Fein Blank Die	1 + \$0.02615 / \$0.00374	7.99

The total complexity is calculated by multiplying the shape complexity of the component by the component's primary and secondary process complexities. The total complexity for each stamped component set is shown in Table 3-11. The shape complexity is from Table 3-8. The total complexity as defined in Figure 2-1 is:

$$C_{\text{Total}} = C_{\text{Shape}} * C_P * (C_{S1} * C_{S2} * \dots * C_{SN}) * C_{\text{material}}$$

Where,

C_{Shape} = geometric shape complexity

C_P = complexity contributed by the primary forming processes

C_{S1}, C_{S2}, C_{SN} = complexities contributed by the finishing processes

C_{Material} = complexity contributed by the material

Table 3-11 Total Complexity for the Stamped Component Set

Component	Shape	Primary	Deburr	Heat-treat	E-Coat	Tumble	Injection	Total Complexity
					Plate		Mold	
1	10.64	1.00	1.18	1.09	3.00	1.11	7.99	363.8
2	7.64	1.00	1.00	1.00	3.00	1.00	1.00	22.9
3	10.51	1.00	1.18	1.09	1.37	1.11	1.00	20.6
4	10.39	1.00	1.00	1.00	3.00	1.00	1.00	31.2
5	14.49	2.33	1.00	1.00	1.16	1.00	1.00	39.2
6	13.45	2.33	1.00	1.00	1.00	1.00	1.00	31.3
7	14.14	2.33	1.00	1.00	1.86	1.00	1.00	61.3
8	52.73	2.33	1.00	1.00	1.16	1.00	1.00	142.5
9	74.64	2.33	1.00	1.00	1.16	1.00	1.00	201.7
10	48.84	2.33	1.00	1.00	1.16	1.00	1.00	132.0

The total complexity of Component 1 is:

$$10.63[\text{shape}] * 1.00[\text{primary}] * 1.18[\text{deburr}] * 1.09[\text{heat-treat}] * 3.0[\text{barrel plate}] * \\ 1.11[\text{tumbling}] * 7.99[\text{injection mold}] = 363.8.$$

The total complexity of Component 2 is:

$$7.64[\text{shape}] * 1.00[\text{primary}] * 3.0[\text{barrel plate}] = 22.9.$$

The total complexity of Component 3 is:

$$10.51[\text{shape}] * 1.00[\text{primary}] * 1.18[\text{deburr}] * 1.09[\text{heat-treat}] * \\ 1.37[\text{plate}] * 1.11[\text{tumbling}] = 20.6.$$

The total complexity of Component 4 is:

$$10.39[\text{shape}] * 1.00[\text{primary}] * 3.0[\text{barrel plate}] = 31.2.$$

The total complexity of Component 5 is:

$$14.49[\text{shape}] * 2.33[\text{primary}] * 1.16[\text{e-coat}] = 39.2.$$

The total complexity of Component 6 is:

$$13.45[\text{shape}] * 2.33[\text{primary}] = 31.3.$$

The total complexity of Component 7 is:

$$14.14[\text{shape}] * 2.33[\text{primary}] * 1.86[\text{barrel plate}] = 61.3.$$

The total complexity of Component 8 is:

$$52.73[\text{shape}] * 2.33[\text{primary}] * 1.16[\text{e-coat}] = 142.5.$$

The total complexity of Component 9 is:

$$74.64[\text{shape}] * 2.33[\text{primary}] * 1.16[\text{e-coat}] = 202.$$

The total complexity of Component 10 is:

$$48.84[\text{shape}] * 2.33[\text{primary}] * 1.16[\text{e-coat}] = 132.$$

To develop the fuzzy sets, the lowest complexity is set to 0.0. The maximum complexity is set to ten percent higher than the highest component complexity. To calculate the low complexity fuzzy set memberships, the smallest component complexity, 20.6, is divided

by each of the other component complexities. The membership of the smallest component is 1.0. The membership of the largest component is 0.028. Table 3-12 shows the initial memberships for each component.

Note the largest component complexity, 400.2, does not have a membership equal to 0.0. This means, the fuzzy set needs to be normalized such that the largest component complexity has a membership of 0.0 in the low complexity fuzzy set. The set is normalized by subtracting 0.051 from all the initial memberships except for 0.0, which remains 1.0. Table 3-13 gives the normalized memberships for each component.

Table 3-12 Initial Memberships of the Low Complexity Fuzzy Set
(Stamped Components)

Component	Complexity	Membership
Minimum	0.000	1.000
1	363.8	0.057
2	22.9	0.898
3	20.6	1.000
4	31.2	0.660
5	39.2	0.667
6	31.3	0.658
7	61.3	0.336
8	142.5	0.145
9	201.7	0.102
10	132.0	0.156
Maximum	400.2	0.051

To calculate the high complexity fuzzy set memberships, the highest complexity, 400.2, is divided into each of the other component complexities. The membership of the largest component is 1.0. The membership of the smallest component is 0.051. Table 3-14 gives the initial memberships for each component in the high complexity fuzzy set.

Table 3-13 Normalized Memberships of the Low Complexity Fuzzy Set
(Stamped Components)

Component	Complexity	Membership
Minimum	0.00	1.000
1	363.8	0.006
2	30.8	0.851
3	20.6	0.949
4	31.2	0.609
5	39.2	0.475
6	31.3	0.607
7	61.3	0.285
8	142.5	0.094
9	202	0.051
10	132	0.105
Maximum	400.2	0.000

Note the smallest component complexity, 20.6, does not have a membership equal to 0.0. This means, the fuzzy set needs to be normalized such that the smallest complexity has a membership of 0.0 in the high complexity fuzzy set. The fuzzy set is normalized by subtracting 0.028 from all the initial memberships. Table 3-15 gives the normalized memberships for each component.

Table 3-14 Initial Memberships of the High Complexity Fuzzy Set

(Stamped Components)

Component	Complexity	Membership
Minimum	0.00	0.000
1	363.8	0.909
2	30.8	0.057
3	20.6	0.051
4	31.2	0.078
5	39.2	0.098
6	31.3	0.078
7	61.3	0.153
8	142.5	0.356
9	201.7	0.505
10	132.0	0.330
Maximum	400.2	1.000

The medium complexity fuzzy set for each component is determined by subtracting the membership of the low complexity fuzzy set and the membership of the high complexity fuzzy set from 1.0. Table 3-16 gives the memberships for the medium complexity set.

**Table 3-15 Normalized Memberships of the High
Complexity Fuzzy Set**

(Stamped Components)

Component	Complexity	Membership
Minimum	0.00	0.000
1	363.8	0.858
2	30.8	0.006
3	20.6	0.000
4	31.2	0.027
5	39.2	0.047
6	31.3	0.027
7	61.3	0.102
8	142.5	0.305
9	201.7	0.454
10	132.0	0.279
Maximum	400.2	0.949

Table 3-16 Component Memberships in the Medium Complexity Fuzzy Set

(Stamped Components)

Component	Complexity	Membership
Minimum	0.00	0.000
1	363.8	0.136
2	22.9	0.147
3	20.6	0.051
4	31.2	0.364
5	39.2	0.478
6	31.3	0.366
7	61.3	0.613
8	142.5	0.601
9	201.7	0.495
10	132.0	0.616
Maximum	400.2	0.051

The cost fuzzy sets are determined from the actual cost of the components. The cost of the component is equal to the material cost and the process cost. The material cost includes the cost of the primary material and the secondary materials used to make the components. The primary material used to make the stamped components is steel. Secondary materials include the cost of the plating, e-coat and injection molded material. Table 3-17 gives the total cost of each component. For the stamping component set, the minimum cost is set to \$0.0. The maximum cost is set to \$0.255 (see Appendix A).

From the flow chart in Section 2.1 the total cost of the component is

$$\text{Cost}_{\text{Total}} = \text{Cost}_{\text{Material}} + \text{Cost}_{\text{Primary}} + \sum \text{Cost}_{\text{Secondary}}$$

The cost of Component 1 is $\$0.031[\text{material}] + \$0.0388[\text{processing}] = \0.0698 .

The cost of Component 2 is $\$0.0293[\text{material}] + \$0.0112[\text{processing}] = \0.0405 .

The cost of Component 3 is $\$0.0407[\text{material}] + \$0.0066[\text{processing}] = \0.0472 .

The cost of Component 4 is $\$0.068[\text{material}] + \$0.0112[\text{processing}] = \0.0792 .

The cost of Component 5 is $\$0.1071[\text{material}] + \$0.0101[\text{processing}] = \0.1172 .

The cost of Component 6 is $\$0.0807[\text{material}] + \$0.0087[\text{processing}] = \0.0894 .

The cost of Component 7 is $\$0.0856[\text{material}] + \$0.0162[\text{processing}] = \0.1019 .

The cost of Component 8 is $\$0.1603[\text{material}] + \$0.0101[\text{processing}] = \0.1704 .

The cost of Component 9 is $\$0.2007[\text{material}] + \$0.0101[\text{processing}] = \0.2108 .

The cost of Component 10 is $\$0.2220[\text{material}] + \$0.0101[\text{processing}] = \$0.2321..$

Table 3-17 Total Cost of Stamped Components

Comp	Primary Material	Secondary Material	Primary	Deburr	Heat-treat	E-Coat Plate	Tumble	Injection Mold	Total Cost
1	0.02604	0.00496	0.00374	0.00067	0.00034	0.00748	0.00043	0.02615	0.069
2	0.02927	0.00	0.00374	0.00	0.00	0.00748	0.00	0.00	0.040
3	0.04067	0.00	0.00374	0.00067	0.00034	0.00138	0.00043	0.00	0.047
4	0.06800	0.00	0.00374	0.00	0.00	0.00748	0.00	0.00	0.079
5	0.07510	0.03200	0.00872	0.00	0.00	0.00138	0.00	0.00	0.117
6	0.08067	0.00	0.00872	0.00	0.00	0.00	0.00	0.00	0.089
7	0.08565	0.00	0.00872	0.00	0.00	0.00748	0.00	0.00	0.101
8	0.12826	0.03200	0.00872	0.00	0.00	0.00138	0.00	0.00	0.170
9	0.16872	0.03200	0.00872	0.00	0.00	0.00138	0.00	0.00	0.210
10	0.19002	0.03200	0.00872	0.00	0.00	0.00138	0.00	0.00	0.232

Table 3-18 Initial Memberships of the Low Cost Fuzzy Set

(Stamped Components)

Component	Cost	Membership
Minimum	\$0.000	1.000
1	\$0.070	0.580
2	\$0.041	1.000
3	\$0.047	0.857
4	\$0.079	0.511
5	\$0.117	0.360
6	\$0.089	0.453
7	\$0.102	0.398
8	\$0.170	0.238
9	\$0.211	0.192
10	\$0.232	0.174
Maximum	\$0.255	0.159

The low cost fuzzy set is developed by dividing the lowest cost, \$0.0405, by each of the other component costs. Table 3-18 gives the initial memberships of each component in the low cost fuzzy set. The set is normalized by subtracting 0.145 from all the memberships. Table 3-19 gives the normalized memberships of each component in the low cost fuzzy set.

**Table 3-19 Normalized Memberships of the Low Cost Fuzzy Set
(Stamped Components)**

Component	Cost	Membership
Minimum	\$0.000	1.000
1	\$0.070	0.421
2	\$0.041	0.841
3	\$0.047	0.698
4	\$0.079	0.352
5	\$0.117	0.201
6	\$0.089	0.294
7	\$0.102	0.239
8	\$0.170	0.079
9	\$0.211	0.033
10	\$0.232	0.015
Maximum	\$0.255	0.000

Table 3-20 Initial Memberships of the High Cost Fuzzy Set
(Stamped Components)

Component	Cost	Membership
Minimum	\$0.000	0.000
1	\$0.070	0.274
2	\$0.041	0.159
3	\$0.047	0.185
4	\$0.079	0.311
5	\$0.117	0.459
6	\$0.089	0.350
7	\$0.102	0.399
8	\$0.170	0.668
9	\$0.211	0.826
10	\$0.232	0.910
Maximum	\$0.255	1.000

The high cost fuzzy set is developed by dividing the highest cost, \$0.255, into each of the other component costs. Table 3-20 gives the initial membership of each component in the high cost fuzzy set. The set is normalized by subtracting 0.159 from all the initial memberships. Table 3-21 gives the normalized memberships of the high cost fuzzy set.

Table 3-21 Normalized Memberships of the High Cost Fuzzy Set
(Stamped Components)

Component	Cost	Membership
Minimum	\$0.000	0.000
1	\$0.070	0.115
2	\$0.041	0.000
3	\$0.047	0.026
4	\$0.079	0.152
5	\$0.117	0.300
6	\$0.089	0.191
7	\$0.102	0.240
8	\$0.170	0.509
9	\$0.211	0.667
10	\$0.232	0.751
Maximum	\$0.255	0.841

The medium cost fuzzy set for each component is determined by subtracting the membership of the low cost fuzzy set and the membership of the high cost fuzzy set from 1.0. Table 3-22 gives the component memberships of the medium cost fuzzy set.

Table 3-22 Component Memberships in the Medium Cost Fuzzy Set
(Stamped Components)

Component	Cost	Membership
Minimum	\$0.000	0.000
1	\$0.070	0.465
2	\$0.041	0.159
3	\$0.047	0.276
4	\$0.079	0.496
5	\$0.117	0.513
6	\$0.089	0.515
7	\$0.102	0.521
8	\$0.170	0.413
9	\$0.211	0.300
10	\$0.232	0.233
Maximum	\$0.255	0.159

3.2.2 Injection Molded Components

The injection-molded component set consists of twenty components. However, due to the large variation in the component sizes the injected molded components are divided into two sets a small set and a large set. The volumes in the small set range from 0.144 in³ to 0.844 in³. The volumes in the large set range from 6.8 in³ to 81.97 in³. Table 3-23 gives the volumes for both the small set and the large set of injection molded components. The minimum component volume in each component set is set to 0.0 in³. The maximum component volume is assumed to be ten percent higher than the largest component volume.

Table 3-23 Volumes of the Injection Molded Component Set

Small Component	Volume	Large Component	Volume
Minimum	0.000 in ³	Minimum	0.00 in ³
1	0.144 in ³	11	6.80 in ³
2	0.175 in ³	12	9.90 in ³
3	0.207 in ³	13	11.30 in ³
4	0.219 in ³	14	21.10 in ³
5	0.354 in ³	15	26.60 in ³
6	0.397 in ³	16	34.79 in ³
7	0.409 in ³	17	56.63 in ³
8	0.599 in ³	18	69.30 in ³
9	0.787 in ³	19	78.47 in ³
10	0.844 in ³	20	81.97 in ³
Maximum	0.928 in ³	Maximum	90.17 in ³

3.2.2.1 Small Injection Molded Components

To calculate the small fuzzy set memberships for the small component set, the smallest component size, 0.144 in³, is divided by each of the other component sizes. The membership of the smallest component is 1.0. The membership of the largest component is 0.155. The set is normalized by subtracting 0.155 from all the initial memberships except for 0.0, which remains 1.0. Table 3-24 shows the normalized memberships for each component in the small injection molded set.

**Table 3-24 Normalized Memberships of the Small Fuzzy Set
(Small Injection Molded Components)**

Component	Volume	Membership
Minimum	0.000	1.000
1	0.144	0.845
2	0.175	0.668
3	0.207	0.541
4	0.219	0.503
5	0.354	0.252
6	0.397	0.208
7	0.409	0.197
8	0.599	0.085
9	0.787	0.028
10	0.844	0.016
Maximum	0.928	0.000

To calculate the large fuzzy set memberships for the small component set, the largest component size, 0.928 in³, is divided into each of the other component sizes. The membership of the largest component is 1.0. The membership of the smallest component is 0.155. The set is normalized by subtracting 0.155 from all the initial memberships except for 0.0, which remains 1.0. Table 3-25 gives the normalized memberships for each component.

The medium fuzzy set for each component is determined by subtracting the membership of the small fuzzy set and the membership of the large fuzzy set from 1.0. Table 3-26 gives the membership of the medium fuzzy set.

The complexity is a function of the shape and the primary process. The injection-molded components do not have secondary processes. Table 3-27 gives the shape complexity for the small injection molded components. The first column under each component contains the geometric dimensions and the second column contains the tolerance on each dimension. The shape complexity is located at the bottom of the first column.

Table 3-25 Normalized Memberships of the Large Fuzzy Set
(Small Injection Molded Components)

Component	Volume	Membership
Minimum	0.000	0.000
1	0.144	0.000
2	0.175	0.033
3	0.207	0.068
4	0.219	0.081
5	0.354	0.226
6	0.397	0.273
7	0.409	0.286
8	0.599	0.490
9	0.787	0.693
10	0.844	0.754
Maximum	0.928	0.845

Table 3-26 Component Memberships in the Medium Fuzzy Set

(Small Injection Molded Components)

Component	Volume	Membership
Minimum	0.000	0.000
1	0.144	0.155
2	0.175	0.299
3	0.207	0.391
4	0.219	0.417
5	0.354	0.522
6	0.397	0.520
7	0.409	0.517
8	0.599	0.424
9	0.787	0.279
10	0.844	0.230
Maximum	0.928	0.155

The processing cost varies with the size of the component and the number of components made at one time. The smaller injection molded components are made eight at a time. The rate for the smallest injection molded component is 794 pieces (pcs) per hour. The larger injection molded components are made two at a time. The rate for the largest injection molded component is 88 pieces (pcs) per hour. The rate for the other components is a function of the component size. A linear function approximates the rates for the other components. The rate is derived as follows:

$$(794 \text{ pcs/hour} - 88 \text{ pcs/hour}) / (0.144 \text{ in}^3 - 82.0 \text{ in}^3) = (794 \text{ pcs/hour} - \text{rate}) / (0.144 \text{ in}^3 - \text{component size})$$

$$- 8.62 \text{ pcs / hr-in}^3 = (794 \text{ pcs/hour} - \text{rate}) / (0.144 \text{ in}^3 - \text{component size})$$

$$-8.62 \text{ pcs / hr-in}^3 * (0.144 \text{ in}^3 - \text{component size}) = (794 \text{ pcs/hour} - \text{rate})$$

$$8.62 \text{ pcs / hr-in}^3 * (\text{component size} - 0.144 \text{ in}^3) = (794 \text{ pcs/hour} - \text{rate})$$

$$\text{Rate} = 794 \text{ pcs/hour} - (8.62 \text{ pcs / hr-in}^3 * (\text{component size} - 0.144 \text{ in}^3))$$

The smallest component processing cost is:

$$0.0131 \text{ \$/pc} = [10.38 \text{ \$ / hr} / (794 \text{ pcs/hour} - (8.628 \text{ pcs / hr-in}^3 * (0.144 \text{ in}^3 - 0.144 \text{ in}^3)))]$$

The largest component processing cost is:

$$0.118 \text{ \$/pc} = [10.38 \text{ \$ / hr} / (794 \text{ pcs/hour} - (8.62 \text{ pcs / hr-in}^3 * (81.97 \text{ in}^3 - 0.144 \text{ in}^3)))]$$

The primary complexity is calculated by dividing the processing cost by the smallest component processing cost. Table 3-28 gives the primary complexities for each component.

Table 3-27 Shape Complexities for the Small Injection Molded Components

Component 1		Component 2		Component 3		Component 4		Component 5	
5.00	5.00	6.00	6.00	6.00	6.00	7.00	7.00	7.00	7.00
1.69	0.06	1.78	0.06	1.91	0.06	1.84	0.06	1.81	0.06
1.63	0.06	1.69	0.06	1.47	0.06	1.09	0.06	0.78	0.06
0.88	0.06	1.03	0.06	1.28	0.06	0.72	0.06	0.78	0.06
0.69	0.06	0.84	0.06	0.91	0.06	0.69	0.06	0.66	0.03
0.19	0.03	0.25	0.03	0.72	0.06	0.56	0.03	0.34	0.03
		0.19	0.03	0.16	0.03	0.16	0.03	0.34	0.03
						0.13	0.03	0.28	0.03
								0.19	0.03
0.79	0.05	0.70	0.05	0.85	0.06	0.52	0.05	0.59	0.04
19.31		22.97		23.55		24.49		26.63	

Component 6		Component 7		Component 8		Component 9		Component 10	
7.00	7.00	8.00	8.00	11.00	11.00	13.00	13.00	13.00	13.00
2.19	0.06	1.75	0.06	4.47	0.06	4.97	0.06	6.22	0.06
0.78	0.06	0.72	0.06	3.31	0.06	1.88	0.06	4.19	0.06
0.78	0.06	0.66	0.03	3.03	0.06	1.56	0.06	3.13	0.03
0.72	0.03	0.53	0.03	2.28	0.06	1.44	0.06	2.75	0.06
0.41	0.03	0.34	0.03	1.97	0.06	1.19	0.06	1.59	0.03
0.38	0.03	0.34	0.03	1.02	0.06	1.19	0.06	1.56	0.06
0.38	0.03	0.28	0.03	0.78	0.06	0.81	0.03	1.06	0.03
0.19	0.03	0.22	0.03	0.72	0.03	0.75	0.06	1.00	0.03
		0.16	0.03	0.50	0.03	0.50	0.03	0.81	0.03
				0.59	0.03	0.44	0.03	0.25	0.03
				0.19	0.03	0.31	0.03	0.25	0.03
						0.25	0.03	0.19	0.03
						0.19	0.03	0.19	0.03
0.66	0.04	0.39	0.02	1.18	0.05	0.80	0.05	1.00	0.04
27.81		32.09		50.68		53.88		61.07	

Table 3-28 Primary Complexities for Small Injection Molded Components
(Small Injection Molded Components)

Component	Volume	Primary Complexity
1	0.144	1.00
2	0.175	1.00
3	0.207	1.00
4	0.219	1.00
5	0.354	1.00
6	0.397	1.00
7	0.409	1.00
8	0.599	1.00
9	0.787	1.01
10	0.844	1.01

The primary complexity for Component 1 is 1.00[(10.38 \$/hr / (794 pcs/hour - (8.628 pieces / hr-in³*(0.144 in³ - 0.144 in³))))/ 0.0131 \$/pcs].

The primary complexity for Component 2 is 1.00 [(10.38 \$/ hr / (794 pcs/hour - (8.628 pieces / hr-in³ *(0.175 in³ - 0.144 in³))))/ 0.0131 \$/pcs].

The primary complexity for Component 3 is 1.00 [(10.38 \$ / hr / (794 pcs/hour-(8.628 pieces / hr-in³*(0.207 in³-0.144 in³))))/ 0.0131 \$/pcs].

The primary complexity for Component 4 is 1.00 [(10.38 \$ / hr / (794 pcs/hour- (8.628 pieces / hr-in³*(0.219 in³-0.144 in³))))/ 0.0131 \$/pcs].

The primary complexity for Component 5 is $1.00[(10.38 \$ / \text{hr} / (794 \text{ pcs/hour} - (8.628 \text{ pieces} / \text{hr-in}^3 * (0.354 \text{ in}^3 - 0.144 \text{ in}^3)))) / 0.0131 \$/\text{pcs}]$.

The primary complexity for Component 6 is $1.00[(10.38 \$ / \text{hr} / (794 \text{ pcs/hour} - (8.628 \text{ pieces} / \text{hr-in}^3 * (0.397 \text{ in}^3 - 0.144 \text{ in}^3)))) / 0.0131 \$/\text{pcs}]$.

The primary complexity for Component 7 is $1.00[(10.38 \$ / \text{hr} / (794 \text{ pcs/hour} - (8.628 \text{ pieces} / \text{hr-in}^3 * (0.409 \text{ in}^3 - 0.144 \text{ in}^3)))) / 0.0131 \$/\text{pcs}]$.

The primary complexity for Component 8 is $1.00[(10.38 \$ / \text{hr} / (794 \text{ pcs/hour} - (8.628 \text{ pieces} / \text{hr-in}^3 * (0.599 \text{ in}^3 - 0.144 \text{ in}^3)))) / 0.0131 \$/\text{pcs}]$.

The primary complexity for Component 9 is $1.01 [(10.38 \$ / \text{hr} / (794 \text{ pcs/hour} - (8.628 \text{ pieces} / \text{hr-in}^3 * (0.787 \text{ in}^3 - 0.144 \text{ in}^3)))) / 0.0131 \$/\text{pcs}]$.

The primary complexity for Component 10 is $1.01 [(10.38 \$ / \text{hr} / (794 \text{ pcs/hour} - (8.628 \text{ pieces} / \text{hr-in}^3 * (0.844 \text{ in}^3 - 0.144 \text{ in}^3)))) / 0.0131 \$/\text{pcs}]$.

Thus, eight out of ten of the primary complexities for the small injection molded components are equal to 1.0. This means that the total complexity for the small injection molded components is controlled by the shape complexity. Table 3-29 gives the total complexity for the small injection molded component set.

Table 3-29 Total Complexities for the Small Injection Molded Components
(Small Injection Molded Components)

Component	Volume	Total Complexity
1	0.144	19.3
2	0.175	23.0
3	0.207	23.6
4	0.219	24.5
5	0.354	26.7
6	0.397	27.9
7	0.409	32.2
8	0.599	50.9
9	0.787	54.3
10	0.844	61.5

The total complexity of Component 1 is $19.31[\text{shape}] * 1.00[\text{primary}] = 19.3$.

The total complexity of Component 2 is $22.97[\text{shape}] * 1.00[\text{primary}] = 23.0$.

The total complexity of Component 3 is $23.55[\text{shape}] * 1.00[\text{primary}] = 23.6$.

The total complexity of Component 4 is $24.49[\text{shape}] * 1.00[\text{primary}] = 24.5$.

The total complexity of Component 5 is $26.63[\text{shape}] * 1.00[\text{primary}] = 26.7$.

The total complexity of Component 6 is $27.81[\text{shape}] * 1.00[\text{primary}] = 27.9$.

The total complexity of Component 7 is $32.09[\text{shape}] * 1.00[\text{primary}] = 32.2$.

The total complexity of Component 8 is $50.68[\text{shape}] * 1.01[\text{primary}] = 50.9$.

The total complexity of Component 9 is $53.88[\text{shape}] * 1.01[\text{primary}] = 54.3$.

The total complexity of Component 10 is $61.07[\text{shape}] * 1.01[\text{primary}] = 61.5$.

To derive the fuzzy sets, the minimum complexity is set to 0.0 and the maximum complexity is assumed to be ten percent higher than the highest complexity.

To calculate the low complexity fuzzy set memberships for the small injection molded component set, the smallest component complexity, 19.3, is divided by each of the other component sizes. The membership of the smallest component is 1.0. The membership of the largest component is 0.285. The complexities are normalized by subtracting 0.285 from each component. Table 3-30 shows the normalized memberships for each component in the low complexity fuzzy set.

Table 3-30 Normalized Memberships of the Low Complexity Fuzzy Set
(Small Injection Molded Components)

Component	Complexity	Membership
Minimum	0.00	1.000
1	19.3	0.715
2	23.0	0.555
3	23.6	0.534
4	24.5	0.503
5	26.7	0.439
6	27.9	0.407
7	32.2	0.315
8	50.9	0.094
9	54.3	0.071
10	61.5	0.029
Maximum	67.7	0.000

To calculate the high complexity fuzzy set memberships for the small injection molded component set, the largest component complexity, 67.8, is divided into each of the other component sizes. The membership of the largest component is 1.0. The membership of the smallest component is 0.285. The complexities are normalized by subtracting 0.285 from each component. Table 3-31 shows the normalized memberships for each component in the high complexity fuzzy set.

The medium complexity fuzzy set for each component is determined by subtracting the membership of the low complexity fuzzy set and the membership of the high complexity fuzzy set from 1.0. Table 3-32 gives the memberships for the medium complexity fuzzy set.

3-31 Normalized Memberships of the High Complexity Fuzzy Set

(Small Injection Molded Components)

Component	Complexity	Membership
Minimum	0.00	0.000
1	19.3	0.000
2	23.0	0.054
3	23.6	0.063
4	24.5	0.077
5	26.7	0.109
6	27.9	0.127
7	32.2	0.190
8	50.9	0.467
9	54.3	0.517
10	61.5	0.624
Maximum	67.7	0.715

The cost fuzzy sets are determined from the actual cost of the small injection-molded components. The cost of the component is equal to the material cost and the process cost. The material used to make the injection-molded components is plastic. Table 3-33 gives the cost of the components in the small injected-molded component set. The minimum cost is set to \$0.0. The maximum cost is set to \$0.086 (see Appendix A).

Table 3-32 Component Memberships in the Medium Complexity Fuzzy Set

(Small Injection Molded Components)

Component	Complexity	Membership
Minimum	0.00	0.000
1	19.3	0.285
2	23.0	0.390
3	23.6	0.402
4	24.5	0.420
5	26.7	0.452
6	27.9	0.466
7	32.2	0.495
8	50.9	0.438
9	54.3	0.413
10	61.5	0.347
Maximum	67.7	0.285

To calculate the low cost fuzzy set memberships for the small injection molded component set, the smallest component cost, \$0.024, is divided by each of the other component costs. The membership of the smallest component is 1.0. The membership of the largest component is 0.283. The complexities are normalized by subtracting 0.283 from each component. Table 3-34 gives the normalized memberships for the low cost fuzzy set.

Table 3-33 Total Cost for the Small Injection Molded Components

Component	Material Cost	Process Cost	Total Cost
1	\$0.011	\$0.013	\$0.024
2	\$0.014	\$0.013	\$0.027
3	\$0.016	\$0.013	\$0.029
4	\$0.017	\$0.013	\$0.030
5	\$0.028	\$0.013	\$0.041
6	\$0.031	\$0.013	\$0.044
7	\$0.032	\$0.013	\$0.045
8	\$0.047	\$0.013	\$0.060
9	\$0.061	\$0.013	\$0.075
10	\$0.066	\$0.013	\$0.079

Table 3-34 Normalized Memberships for the Low Cost Fuzzy Set

(Small Injection Molded Components)

Component	Cost	Membership
Minimum	0.000	1.000
1	\$0.024	0.717
2	\$0.027	0.627
3	\$0.029	0.549
4	\$0.030	0.523
5	\$0.041	0.314
6	\$0.044	0.269
7	\$0.045	0.257
8	\$0.060	0.123
9	\$0.075	0.043
10	\$0.079	0.025
Maximum	\$0.086	0.000

To calculate the high cost fuzzy set, the highest component cost, \$0.086, is divided into each of the other component costs. The membership of the largest component is 1.0. The membership of the smallest component is 0.283. The complexities are normalized by subtracting 0.283 from each component. Table 3-35 gives the normalized memberships for the high cost fuzzy set.

Table 3-35 Normalized Memberships for the High Cost Fuzzy Set
(Small Injection Molded Components)

Component	Cost	Membership
Minimum	0.000	0.000
1	\$0.024	0.000
2	\$0.027	0.028
3	\$0.029	0.057
4	\$0.030	0.068
5	\$0.041	0.191
6	\$0.044	0.230
7	\$0.045	0.241
8	\$0.060	0.413
9	\$0.075	0.584
10	\$0.079	0.636
Maximum	\$0.086	0.717

The medium cost fuzzy set for each component is determined by subtracting the membership of the low cost fuzzy set and the membership of the high cost fuzzy set from 1.0. Table 3-36 gives the memberships for the medium cost fuzzy set.

Table 3-36 Component Memberships in the Medium Cost Fuzzy Set
(Small Injection Molded Components)

Component	Cost	Membership
Minimum	0.000	0.000
1	\$0.024	0.283
2	\$0.027	0.345
3	\$0.029	0.394
4	\$0.030	0.409
5	\$0.041	0.495
6	\$0.044	0.501
7	\$0.045	0.502
8	\$0.060	0.463
9	\$0.075	0.373
10	\$0.079	0.339
Maximum	\$0.086	0.283

3.2.2.2 Large Injection Molded Components

To calculate the low size fuzzy set memberships for the large injection molded component set, the smallest component size, 6.8 in³, is divided by each of the other component sizes. The membership of the smallest component 6.8 in³ is equal to 1.0. The membership of the largest component is 0.075. The set is normalized by subtracting 0.075 from the initial memberships. Table 3-37 gives the normalized memberships for the small size fuzzy set.

Table 3-37 Normalized Memberships for the Small Fuzzy Set

(Large Injection Molded Components)

Component	Volume	Membership
Minimum	0.00	1.000
11	6.80	0.925
12	9.90	0.612
13	11.3	0.527
14	21.1	0.247
15	26.6	0.181
16	34.8	0.120
17	56.6	0.045
18	69.3	0.023
19	78.5	0.012
20	82.0	0.008
Maximum	90.2	0.000

To calculate the large size fuzzy set memberships, the highest component size, 90.2 in³, is divided into each of the other component sizes. The highest component membership is equal to 1.0. The initial membership of the lowest component size is 0.075. The set is normalized by subtracting 0.075 from the initial memberships. Table 3-38 gives the normalized memberships for the large size fuzzy set.

The medium fuzzy set for each component is determined by subtracting the membership of the small fuzzy set and the membership of the large fuzzy set from 1.0. Table 3-39 gives the memberships for the medium fuzzy set.

Table 3-38 Normalized Memberships for the Large Fuzzy Set**(Large Injection Molded Components)**

Component	Volume	Membership
Minimum	0.00	0.000
11	6.80	0.000
12	9.90	0.035
13	11.3	0.050
14	21.1	0.159
15	26.6	0.220
16	34.8	0.311
17	56.6	0.553
18	69.3	0.694
19	78.5	0.795
20	82.0	0.834
Maximum	90.2	0.925

The complexity for the large injection molded components is calculated using the same equations used for the small injection molded components. The complexity is a function of the shape and process complexity. Table 3-40 gives the shape complexity for the large injection molded components. The first column under each component contains the geometric dimensions and the second column contains the tolerance on each dimension. The shape complexity is located at the bottom of the first column. The shape complexity is located at the bottom of the first column.

Table 3-39 Memberships in the Medium Fuzzy Set

(Large Injection Molded Components)

Component	Volume	Membership
Minimum	0.00	0.000
11	6.80	0.075
12	9.90	0.353
13	11.3	0.423
14	21.1	0.594
15	26.6	0.599
16	34.8	0.569
17	56.6	0.402
18	69.3	0.283
19	78.5	0.193
20	82.0	0.158
Maximum	90.2	0.075

The processing cost varies with the size of the component and the number of components made at one time. The smaller injection molded components are made eight at a time. The rate for the smallest injection molded component is 794 pieces (pcs) per hour. The larger injection molded components are made two at a time. The rate for the largest injection molded component is 88 pieces (pcs) per hour. The rate for the other components is a function of the component size. A linear function approximates the rates for the other components. The rate is derived as follows:

$$(794 \text{ pcs/hour} - 88 \text{ pcs/hour}) / (0.144 \text{ in}^3 - 82.0 \text{ in}^3) = (794 \text{ pcs/hour} - \text{rate}) / (0.144 \text{ in}^3 - \text{volume})$$

$$- 8.62 \text{ pcs / hr-in}^3 = (794 \text{ pcs/hour} - \text{rate}) / (0.144 \text{ in}^3 - \text{volume})$$

$$-8.62 \text{ pcs / hr-in}^3 * (0.144 \text{ in}^3 - \text{volume}) = (794 \text{ pcs/hour} - \text{rate})$$

$$8.62 \text{ pcs / hr-in}^3 * (\text{volume} - 0.144 \text{ in}^3) = (794 \text{ pcs/hour} - \text{rate})$$

$$\text{rate} = 794 \text{ pcs/hour} - (8.62 \text{ pcs / hr-in}^3 * (\text{volume} - 0.144 \text{ in}^3))$$

The smallest component processing cost is:

$$0.0131 \text{ \$/pc} = [10.38 \text{ \$ / hr} / (794 \text{ pcs/hour} - (8.628 \text{ pcs / hr-in}^3 * (0.144 \text{ in}^3 - 0.144 \text{ in}^3)))]$$

The largest component processing cost is:

$$0.118 \text{ \$/pc} = [10.38 \text{ \$ / hr} / (794 \text{ pcs/hour} - (8.62 \text{ pcs / hr-in}^3 * (81.97 \text{ in}^3 - 0.144 \text{ in}^3)))]$$

The primary complexity is calculated by dividing the processing cost by the smallest component processing cost. Table 3-41 gives the primary complexities for each component. The primary complexity for the large injection molded components does affect the total complexity. This occurs because larger components require additional handling and fewer are made at one time. Table 3-42 gives the total complexities for the large injection molded component set.

The total complexity of Component 11 is $46.37[\text{shape}] * 1.08[\text{primary}] = 50.0$.

The total complexity of Component 12 is $44.78[\text{shape}] * 1.12[\text{primary}] = 50.1$.

The total complexity of Component 13 is $44.03[\text{shape}] * 1.14[\text{primary}] = 50.1$.

The total complexity of Component 14 is $63.87[\text{shape}] * 1.29[\text{primary}] = 82.7$.

The total complexity of Component 15 is $65.76[\text{shape}] * 1.40[\text{primary}] = 92.3$.

The total complexity of Component 16 is $70.18[\text{shape}] * 1.60[\text{primary}] = 112.5$.

The total complexity of Component 17 is $75.90[\text{shape}] * 2.59[\text{primary}] = 196.2$.

The total complexity of Component 18 is $78.07[\text{shape}] * 4.01[\text{primary}] = 313.3$.

The total complexity of Component 19 is $80.37[\text{shape}] * 6.68[\text{primary}] = 537.0$.

The total complexity of Component 20 is $92.24[\text{shape}] * 8.96[\text{primary}] = 826.1$.

Table 3-40 Shape Complexities
(Large Injection Molded Components)

Component 1		Component 2		Component 3		Component 4		Component 5	
10.00	10.00	10.00	10.00	9.00	9.00	13.00	13.00	13.00	13.00
8.72	0.06	10.44	0.06	13.06	0.06	12.47	0.06	22.13	0.06
6.31	0.06	7.00	0.06	9.94	0.06	7.72	0.06	8.13	0.06
5.31	0.06	3.06	0.06	3.69	0.06	3.41	0.06	5.63	0.06
1.50	0.06	1.50	0.06	1.50	0.06	2.36	0.06	3.16	0.06
1.31	0.06	0.75	0.06	1.06	0.06	2.09	0.06	2.00	0.06
0.75	0.06	0.75	0.06	0.75	0.06	2.03	0.06	1.97	0.06
0.50	0.03	0.50	0.03	0.50	0.03	1.81	0.06	1.56	0.06
0.31	0.03	0.29	0.03	0.29	0.03	1.33	0.06	1.28	0.06
0.31	0.03	0.25	0.03	0.25	0.03	1.09	0.06	1.28	0.06
0.25	0.03	0.25	0.03			0.78	0.06	1.06	0.06
						0.53	0.03	1.00	0.06
						0.50	0.03	0.81	0.06
						0.25	0.03	0.25	0.03
1.18	0.05	1.06	0.05	1.45	0.05	1.60	0.05	1.98	0.06
46.37		44.78		44.03		63.87		65.76	

Component 6		Component 7		Component 8		Component 9		Component 10	
13.00	13.00	13.00	13.00	14.00	14.00	14.00	14.00	14.00	14.00
28.25	0.06	30.94	0.06	34.13	0.06	35.88	0.06	36.13	0.06
25.13	0.06	27.56	0.06	28.88	0.06	26.94	0.06	23.28	0.06
14.63	0.06	18.09	0.06	18.47	0.06	19.63	0.06	22.80	0.06
10.19	0.06	6.38	0.06	10.06	0.06	12.17	0.06	18.09	0.06
1.81	0.06	5.19	0.06	7.84	0.06	8.97	0.06	16.34	0.06
1.69	0.06	4.84	0.06	2.75	0.06	7.52	0.06	11.38	0.06
1.63	0.06	3.75	0.06	2.00	0.06	4.97	0.06	9.84	0.06
1.56	0.06	2.75	0.06	1.69	0.06	2.25	0.06	7.94	0.06
1.06	0.06	2.06	0.06	1.06	0.06	0.94	0.06	7.69	0.06
0.97	0.06	0.88	0.06	0.97	0.06	0.75	0.06	6.52	0.06
0.94	0.06	0.88	0.06	0.94	0.06	0.75	0.06	1.25	0.06
0.75	0.06	0.78	0.06	0.84	0.06	0.69	0.06	0.75	0.06
0.25	0.03	0.25	0.03	0.81	0.06	0.69	0.06	0.69	0.06
				0.25	0.03	0.25	0.03	0.25	0.03
2.50	0.06	3.39	0.06	2.84	0.06	3.18	0.06	5.73	0.06
70.18		75.90		78.07		80.37		92.24	

Table 3-41 Primary Complexities**(Large Injection Molded Components)**

Component	Volume	Primary Complexity
11	6.80	1.08
12	9.90	1.12
13	11.3	1.14
14	21.1	1.29
15	26.6	1.40
16	34.8	1.60
17	56.6	2.59
18	69.3	4.01
19	78.5	6.68
20	82.0	8.96

Table 3-42 Total Complexities**(Large Injection Molded Components)**

Component	Total Complexity
Minimum	0.0
11	50.0
12	50.1
13	50.1
14	82.7
15	92.3
16	112.5
17	196.2
18	313.3
19	537.0
20	826.1
Maximum	908.7

The minimum complexity is set to 0.0. The maximum complexity is set to ten percent over the highest component complexity. To calculate the low complexity fuzzy set memberships, the lowest complexity, 50, is divided by each of the other component complexities. The lowest complexity membership is equal to 1.0. The initial membership of the highest complexity is 0.055. The set is normalized by subtracting 0.055 from each of the initial memberships. Table 3-43 gives the normalized memberships for the low complexity fuzzy set.

Table 3-43 Memberships for the Low Complexity Fuzzy Set
(Large Injection Molded Components)

Component	Complexity	Membership
Minimum	0.0	1.000
11	50.0	0.945
12	50.1	0.943
13	50.1	0.943
14	82.7	0.550
15	92.3	0.487
16	112.5	0.444
17	196.2	0.200
18	313.3	0.105
19	537.0	0.038
20	826.1	0.006
Maximum	908.7	0.000

To calculate the high complexity fuzzy set memberships, the maximum complexity, 908.7, is divided into each of the other complexities. The initial membership of the lowest complexity is 0.055. The set is normalized by subtracting 0.055 from each of the initial memberships. Table 3-44 gives the normalized memberships for the high complexity fuzzy set.

Table 3-44 Memberships for the High Complexity Fuzzy Set

Large Injection Molded Components		
Component	Complexity	Membership
Minimum	0.0	0.000
11	50.0	0.000
12	50.1	0.000
13	50.1	0.000
14	82.7	0.036
15	92.3	0.047
16	112.5	0.124
17	196.2	0.161
18	313.3	0.290
19	537.0	0.536
20	826.1	0.854
Maximum	908.7	0.945

The medium complexity fuzzy set for each component is determined by subtracting the membership of the low complexity fuzzy set and the membership of the high complexity fuzzy set from 1.0. Table 3-45 gives the memberships for the medium complexity fuzzy set.

Table 3-45 Memberships in the Medium Complexity Fuzzy Set
(Large Injection Molded Components)

Component	Complexity	Membership
Minimum	0.0	0.000
11	50.0	0.070
12	50.1	0.107
13	50.1	0.161
14	82.7	0.275
15	92.3	0.345
16	112.5	0.447
17	196.2	0.598
18	313.3	0.591
19	537.0	0.430
20	826.1	0.153
Maximum	908.7	0.070

The cost fuzzy sets are determined from the actual cost of the large injection molded components. The cost of the component is equal to the material cost and the process cost. The material used to make the injection-molded components is plastic. Table 3-46 gives the total cost for the large injection molded component set. The minimum cost is set to \$0.0. The maximum cost is set to \$6.83 (see Appendix A).

Table 3-46 Total Costs for Large Injection Molded Component Set

Component	Material Cost	Process Cost	Total Cost
11	\$0.530	\$0.014	\$0.544
12	\$0.772	\$0.015	\$0.787
13	\$0.881	\$0.015	\$0.896
14	\$1.645	\$0.017	\$1.662
15	\$2.074	\$0.018	\$2.092
16	\$2.713	\$0.021	\$2.734
17	\$4.415	\$0.034	\$4.449
18	\$5.403	\$0.053	\$5.456
19	\$6.118	\$0.088	\$6.206
20	\$6.391	\$0.118	\$6.509

To calculate the low cost fuzzy set memberships, the lowest cost component, \$0.544, is divided by each of the other complexities. The initial membership of the lowest cost component is 0.080. The set is normalized by subtracting 0.080 from each of the initial memberships. Table 3-47 gives the normalized memberships for the low cost fuzzy.

Table 3-47 Normalized Memberships for the Low Cost Fuzzy Set
(Large Injection Molded Components)

Component	Cost	Membership
Minimum	\$0.000	1.000
11	\$0.544	0.920
12	\$0.787	0.612
13	\$0.896	0.528
14	\$1.662	0.247
15	\$2.092	0.180
16	\$2.734	0.119
17	\$4.449	0.042
18	\$5.456	0.020
19	\$6.206	0.008
20	\$6.509	0.004
Maximum	\$6.830	0.000

To calculate the high cost fuzzy set memberships, the maximum cost component, \$6.83, is divided into each of the other complexities. The initial membership of the lowest cost component is 0.080. The set is normalized by subtracting 0.080 from each of the initial memberships. Table 3-48 gives the normalized memberships for the high cost fuzzy set.

Table 3-48 Memberships for the High Cost Fuzzy Set
(Large Injection Molded Components)

Component	Cost	Membership
Minimum	\$0.000	0.000
11	\$0.544	0.000
12	\$0.787	0.035
13	\$0.896	0.051
14	\$1.662	0.163
15	\$2.092	0.226
16	\$2.734	0.320
17	\$4.449	0.571
18	\$5.456	0.719
19	\$6.206	0.829
20	\$6.509	0.873
Maximum	\$6.830	0.920

The medium cost fuzzy set for each component is determined by subtracting the membership of the low cost fuzzy set and the membership of the high cost fuzzy set from 1.0. Table 3-49 gives the medium cost fuzzy set memberships for the large injection molded components.

Table 3-49 Memberships in the Medium Cost Fuzzy Set
(Large Injection Molded Components)

Component	Cost	Medium
Minimum	\$0.000	0.000
11	\$0.544	0.080
12	\$0.787	0.353
13	\$0.896	0.421
14	\$1.662	0.589
15	\$2.092	0.594
16	\$2.734	0.561
17	\$4.449	0.386
18	\$5.456	0.261
19	\$6.206	0.164
20	\$6.509	0.123
Maximum	\$6.830	0.080

3.2.3 Extruded Components

The extruded component set consists of ten components. There are five steel components and five aluminum components. Table 3-50 gives the material and volume of each component. The minimum volume is 0.0 in³. The maximum volume is set to ten percent higher than the highest volume or 7.812 in³.

Table 3-50 Volume and Material of Extruded Component Set

Component	Length	Material	Volume
1	8.375	Steel	0.556 in ³
2	11.25	Steel	1.335 in ³
3	17.25	Steel	1.887 in ³
4	13.875	Aluminum	2.989 in ³
5	18.25	Aluminum	3.778 in ³
6	42.25	Steel	3.961 in ³
7	47.00	Steel	4.406 in ³
8	26.50	Aluminum	5.176 in ³
9	34.75	Aluminum	6.108 in ³
10	37.875	Aluminum	7.102 in ³

To calculate the small fuzzy set memberships, the lowest volume component, 0.556 in³, is divided by each of the other component sizes. The initial membership of the highest component size is 0.071. The set is normalized by subtracting 0.071 from each of the initial memberships. Table 3-51 gives the normalized memberships for the small fuzzy set.

Table 3-51 Normalized Memberships for the Small Fuzzy Set
(Extruded Components)

Component	Length	Material	Volume	Memberships
Minimum			0.000 in ³	1.000
1	8.375	Steel	0.556 in ³	0.929
2	11.25	Steel	1.335 in ³	0.339
3	17.25	Steel	1.887 in ³	0.223
4	13.875	Aluminum	2.989 in ³	0.115
5	18.25	Aluminum	3.778 in ³	0.076
6	42.25	Steel	3.961 in ³	0.069
7	47.00	Steel	4.406 in ³	0.055
8	26.50	Aluminum	5.176 in ³	0.036
9	34.75	Aluminum	6.108 in ³	0.020
10	37.875	Aluminum	7.102 in ³	0.007
Maximum			7.812 in ³	0.000

To calculate the large fuzzy set memberships, the highest volume component, 7.812 in³, is divided by each of the other component sizes. The initial membership of the lowest component size is 0.071. The set is normalized by subtracting 0.071 from each of the initial memberships. Table 3-52 gives the normalized memberships for the large fuzzy set.

The medium fuzzy set for each component is determined by subtracting the membership of the small fuzzy set and the membership of the large fuzzy set from 1.0. Table 3-53 gives the memberships for the medium fuzzy set.

Table 3-52 Normalized Memberships for the Large Fuzzy Set
(Extruded Components)

Component	Length	Material	Volume	Memberships
Minimum			0.000 in ³	0.000
1	8.375	Steel	0.556 in ³	0.000
2	11.25	Steel	1.335 in ³	0.102
3	17.25	Steel	1.887 in ³	0.170
4	13.875	Aluminum	2.989 in ³	0.311
5	18.25	Aluminum	3.778 in ³	0.412
6	42.25	Steel	3.961 in ³	0.436
7	47.00	Steel	4.406 in ³	0.493
8	26.50	Aluminum	5.176 in ³	0.591
9	34.75	Aluminum	6.108 in ³	0.711
10	37.875	Aluminum	7.102 in ³	0.838
Maximum			7.812 in ³	0.929

The complexity of the extruded components is a function of the geometric shape, the primary process and the material. The shape complexity for each component is shown in Table 3-54. The first column under each component contains the geometric dimensions and the second column contains the tolerance on each dimension. The shape complexity is located at the bottom of the first column.

The primary complexity is a function of the length of the component, the processing rate of the extrusion press and the material. The shortest steel component is 8.375 inches long. The shortest aluminum component is 13.875 inches long.

The extrusion rate for the steel components is:

$$13,680 \text{ inches / hour} = [20 \text{ feet/minute} * 12 \text{ inches/foot} * 57 \text{ minutes / hour}].$$

Table 3-53 Memberships in the Medium Fuzzy Set

(Extruded Components)

Component	Length	Material	Volume	Medium
Minimum			0.000 in ³	0.000
1	8.375	Steel	0.556 in ³	0.071
2	11.25	Steel	1.335 in ³	0.559
3	17.25	Steel	1.887 in ³	0.606
4	13.875	Aluminum	2.989 in ³	0.574
5	18.25	Aluminum	3.778 in ³	0.512
6	42.25	Steel	3.961 in ³	0.495
7	47.00	Steel	4.406 in ³	0.452
8	26.50	Aluminum	5.176 in ³	0.372
9	34.75	Aluminum	6.108 in ³	0.269
10	37.875	Aluminum	7.102 in ³	0.155
Maximum			7.812 in ³	0.071

The extrusion rate for the aluminum components is:

$$37,620 \text{ inches / hour} = [55 \text{ feet/minute} * 12 \text{ inches/foot} * 57 \text{ minutes / hour}].$$

The cost per inch for steel is:

$$\$0.00076 = [10.38 \text{ \$/hour} / 13680 \text{ inches/hour}].$$

The cost per inch for aluminum is:

$$\$0.00028 = [10.38 \text{ \$/hour} / 37,620 \text{ inches/hour}].$$

The shortest steel component has a cost of:

$$\$0.00635 = [0.00076 \text{ \$/inch} * 8.375 \text{ inches}].$$

The shortest aluminum component has a cost of:

$$\$0.00383 = [0.00028 \text{ \$/inch} * 13.875 \text{ inches}].$$

Table 3-54 Shape Complexities for the Extruded Component Set

Component 1		Component 2		Component 3		Component 4		Component 5	
5.00	5.00	5.00	5.00	6.00	6.00	5.00	5.00	6.00	6.00
8.38	0.06	11.25	0.06	13.88	0.06	17.25	0.06	18.25	0.06
1.06	0.06	1.19	0.06	2.06	0.06	1.75	0.06	3.31	0.06
0.75	0.06	0.50	0.06	0.69	0.06	0.75	0.06	0.94	0.06
0.25	0.03	0.31	0.03	0.19	0.03	0.56	0.06	0.50	0.06
0.06	0.03	0.06	0.03	0.13	0.03	0.06	0.03	0.19	0.03
				0.06	0.03			0.06	0.03
0.64	0.05	0.67	0.05	0.55	0.04	0.96	0.05	0.83	0.05
18.74		19.06		21.88		20.67		24.41	

Component 6		Component 7		Component 8		Component 9		Component 10	
7.00	7.00	7.00	7.00	6.00	6.00	6.00	6.00	6.00	6.00
42.25	0.06	47.00	0.06	26.50	0.06	34.75	0.06	37.88	0.06
1.50	0.06	1.50	0.06	3.13	0.06	2.81	0.06	3.00	0.06
1.19	0.06	1.19	0.06	0.94	0.06	1.63	0.06	2.06	0.06
1.06	0.06	0.94	0.06	0.44	0.03	0.69	0.06	0.94	0.06
0.75	0.06	0.88	0.06	0.19	0.03	0.25	0.03	0.25	0.03
0.44	0.03	0.50	0.03	0.06	0.03	0.06	0.03	0.06	0.03
0.06	0.03	0.06	0.03						
1.59	0.08	1.66	0.08	0.86	0.04	1.09	0.05	1.23	0.05
29.71		30.10		25.67		26.77		27.78	

The primary complexity for each component is calculated by dividing the component process cost by the smallest component process cost. The shortest aluminum component has the lowest process cost. Table 3-55 gives the primary complexity for each component in the extruded component set.

Table 3-55 Primary Complexity of the Extruded Component Set

Component	Length	Material	Process Cost	Primary Complexity
1	8.375	Steel	0.006	1.64
2	11.25	Steel	0.009	1.90
3	13.875	Aluminum	0.004	1.00
4	17.25	Steel	0.013	3.37
5	18.25	Aluminum	0.005	1.31
6	42.25	Steel	0.032	8.25
7	47.00	Steel	0.036	9.18
8	26.50	Aluminum	0.007	1.91
9	34.75	Aluminum	0.010	2.50
10	37.875	Aluminum	0.011	2.73

The primary complexity of Component 1 is $[(0.00076 * 8.375) / 0.00383] = 1.64$

The primary complexity of Component 2 is $[(0.00076 * 11.25) / 0.00383] = 1.90$.

The primary complexity of Component 3 is $[(0.00028 * 13.875) / 0.00383] = 1.00$.

The primary complexity of Component 4 is $[(0.00076 * 17.25) / 0.00383] = 3.37$.

The primary complexity of Component 5 is $[(0.00028 * 18.25) / 0.00383] = 1.31$.

The primary complexity of Component 6 is $[(0.00076 * 42.25) / 0.00383] = 8.25$.

The primary complexity of Component 7 is $[(0.00076 * 47.00) / 0.00383] = 9.18$.

The primary complexity of Component 8 is $[(0.00028 * 26.5) / 0.00383] = 1.91$.

The primary complexity of Component 9 is $[(0.00028 * 34.75) / 0.00383] = 2.50$.

The primary complexity of Component 10 is $[(0.00028 * 37.875) / 0.00383] = 2.73$.

The secondary complexity is equal to 1.0 for all of the components in the extruded component set. Additional secondary processes are not performed to make the components. As stated in Section 2.0, if a set of components has more than one material, the material complexity is $C_{\text{material}} = \text{LCM} / \text{HMC}$ for the lower cost material i.e. the high cost material divided by the low cost material. The cost of the steel is \$0.76 and the cost of the aluminum is \$1.137. Thus, steel is the lower cost material.

$$C_{\text{aluminum}} = \$0.76 / \$0.76 = 1.00$$

$$C_{\text{steel}} = \$0.76 / \$1.137 = 0.67$$

The total complexity as defined in Figure 2.2-1 is:

$$C_{\text{Total}} = C_{\text{Shape}} * C_{\text{P}} * (C_{\text{S1}} * C_{\text{S2}} * \dots * C_{\text{SN}}) * C_{\text{material}}$$

Where, C_{Shape} = geometric shape complexity

C_{P} = complexity contributed by the primary forming processes

$C_{\text{S1}}, C_{\text{S2}}, C_{\text{SN}}$ = complexities contributed by the finishing processes

C_{Material} = complexity contributed by the material

The total complexity of Component 1 is:

$$18.74[\text{shape}] * 1.64[\text{primary}] * 0.67[\text{material}] = 20.5.$$

The total complexity of Component 2 is:

$$19.06[\text{shape}] * 1.9[\text{primary}] * 0.67[\text{material}] = 24.3.$$

The total complexity of Component 3 is:

$$21.85[\text{shape}] * 1.00[\text{primary}] * 1.00[\text{material}] = 21.9.$$

The total complexity of Component 4 is:

$$20.67[\text{shape}] * 3.37[\text{primary}] * 0.67[\text{material}] = 46.6.$$

The total complexity of Component 5 is:

$$24.41[\text{shape}] * 1.31[\text{primary}] * 1.00[\text{material}] = 32.1.$$

The total complexity of Component 6 is:

$$29.71[\text{shape}] * 8.25[\text{primary}] * 0.67[\text{material}] = 163.9.$$

The total complexity of Component 7 is:

$$30.1[\text{shape}] * 9.18[\text{primary}] * 0.67[\text{material}] = 184.8.$$

The total complexity of Component 8 is:

$$25.67[\text{shape}] * 1.91[\text{primary}] * 1.00[\text{material}] = 49.0.$$

The total complexity of Component 9 is:

$$26.77[\text{shape}] * 2.5[\text{primary}] * 1.00[\text{material}] = 67.0.$$

The total complexity Component 10 is:

$$27.78[\text{shape}] * 2.73[\text{primary}] * 0.67[\text{material}] = 50.8.$$

The minimum complexity is set to 0.0. The maximum complexity is set to ten percent higher than the highest complexity. Table 3-56 gives the total complexity for each component.

To calculate the low complexity fuzzy set memberships, the lowest complexity, 20.5, is divided by each of the other component complexities. The set is normalized by subtracting 0.101 from each of the initial memberships. Table 3-57 gives the normalized memberships for the low complexity fuzzy set.

Table 3-56 Total Complexity of the Extruded Component Set

Component	Length	Material	Shape Complexity	Primary Complexity	Material Complexity	Total Complexity
1	8.375	Steel	18.74	1.64	0.67	20.5
2	11.25	Steel	19.06	1.90	0.67	24.3
3	13.875	Aluminum	21.88	1.00	1.00	21.9
4	17.25	Steel	20.67	3.37	0.67	46.7
5	18.25	Aluminum	24.41	1.31	1.00	32.1
6	42.25	Steel	29.71	8.25	0.67	163.9
7	47.00	Steel	30.1	9.18	0.67	184.8
8	26.50	Aluminum	25.67	1.91	1.00	49.0
9	34.75	Aluminum	26.77	2.50	1.00	67.0
10	37.875	Aluminum	27.78	2.73	0.67	50.8

Table 3-57 Normalized Memberships for the Low Complexity Fuzzy Set**(Extruded Component Set)**

Component	Complexity	Memberships
Minimum	0.00	1.000
1	20.5	0.899
2	24.3	0.744
3	46.6	0.339
4	21.9	0.837
5	32.1	0.538
6	163.9	0.024
7	184.8	0.010
8	49.0	0.318
9	67.0	0.205
10	75.7	0.170
Maximum	203.2	0.000

To calculate the high complexity fuzzy set memberships, the highest complexity, 184.75, is divided into each of the other component complexities. The initial membership of the lowest component complexity is 0.101. The set is normalized by subtracting 0.040 from each of the initial memberships. Table 3-58 gives the normalized memberships for the high complexity fuzzy set.

Table 3-58 Normalized Memberships for the High Complexity Fuzzy Set

(Extruded Component Set)

Component	Complexity	Memberships
Minimum	0.00	0.000
1	20.5	0.000
2	24.3	0.019
3	46.6	0.128
4	21.9	0.007
5	32.1	0.057
6	163.9	0.706
7	184.8	0.808
8	49.0	0.140
9	67.0	0.229
10	75.7	0.272
Maximum	203.2	0.899

The medium complexity fuzzy set for each component is determined by subtracting the membership of the low complexity fuzzy set and the membership of the high complexity fuzzy set from 1.0. Table 3-59 gives the complexity of the medium complexity fuzzy set.

The cost fuzzy sets are determined from the actual cost of the components. The cost of the component is equal to the material cost and the process cost. Table 3-60 gives the total cost of each component. The minimum cost is set to \$0.0. The maximum cost for the extruded component set is \$1.121 (see Appendix A).

Table 3-59 Memberships in the Medium Complexity Fuzzy Set

(Extruded Components)

Component	Complexity	Membership
Minimum	0.00	0.000
1	20.5	0.101
2	24.3	0.238
3	46.6	0.532
4	21.9	0.156
5	32.1	0.405
6	163.9	0.270
7	184.8	0.182
8	49.0	0.542
9	67.0	0.566
10	75.7	0.558
Maximum	203.2	0.101

Table 3-60 Total Cost of the Extruded Component Set

Component	Length	Material	Material Cost	Process Cost	Total Cost
1	8.375	Steel	\$0.120	\$0.006	\$0.126
2	11.25	Steel	\$0.291	\$0.009	\$0.300
3	13.875	Aluminum	\$0.333	\$0.004	\$0.337
4	17.25	Steel	\$0.406	\$0.013	\$0.419
5	18.25	Aluminum	\$0.421	\$0.005	\$0.426
6	42.25	Steel	\$0.852	\$0.032	\$0.884
7	47.00	Steel	\$0.948	\$0.036	\$0.983
8	26.50	Aluminum	\$0.577	\$0.007	\$0.584
9	34.75	Aluminum	\$0.681	\$0.010	\$0.690
10	37.875	Aluminum	\$0.791	\$0.011	\$0.802

To calculate the low cost fuzzy set memberships, the lowest cost component, \$0.126, is divided by each of the other component costs. The initial membership of the highest component cost is 0.112. The set is normalized by subtracting 0.112 from each of the initial memberships. Table 3-61 gives the normalized memberships for the low cost fuzzy set.

Table 3-61 Normalized Memberships for the Low Cost Fuzzy Set
(Extruded Components)

Component	Cost	Memberships
Minimum	\$0.000	1.000
1	\$0.126	0.888
2	\$0.300	0.308
3	\$0.419	0.189
4	\$0.337	0.262
5	\$0.426	0.184
6	\$0.884	0.030
7	\$0.983	0.016
8	\$0.584	0.104
9	\$0.690	0.070
10	\$0.802	0.045
Maximum	\$1.121	0.000

To calculate the high cost fuzzy set memberships, the maximum cost, \$1.121, is divided into each of the other component costs. The initial membership of the lowest cost is 0.112. The set is normalized by subtracting 0.112 from each of the initial memberships. Table 3-62 gives the normalized memberships for the high cost fuzzy set.

Table 3-62 Normalized Memberships for the High Cost Fuzzy Set
(Extruded Components)

Component	Cost	Memberships
Minimum	\$0.000	0.000
1	\$0.126	0.000
2	\$0.300	0.156
3	\$0.419	0.262
4	\$0.337	0.189
5	\$0.426	0.268
6	\$0.884	0.677
7	\$0.983	0.765
8	\$0.584	0.409
9	\$0.690	0.504
10	\$0.802	0.603
Maximum	\$1.121	0.888

The medium fuzzy set for each component is determined by subtracting the membership of the small fuzzy set and the membership of the large fuzzy set from 1.0. Table 3-63 gives the memberships for the medium cost fuzzy set.

Table 3-63 Memberships in the Medium Cost Fuzzy Set

(Extruded Components)

Component	Cost	Medium
Minimum	\$0.000	0.000
1	\$0.126	0.092
2	\$0.300	0.545
3	\$0.419	0.577
4	\$0.337	0.564
5	\$0.426	0.577
6	\$0.884	0.396
7	\$0.983	0.338
8	\$0.584	0.542
9	\$0.690	0.498
10	\$0.802	0.442
Maximum	\$1.370	0.092

3.2.4 Rolled Components

The rolled component set consists of ten components. There are five steel components and five aluminum components. The minimum volume is set to 0.0 in^3 . The maximum volume is set to ten percent higher than the highest component volume or 14.318 in^3 . Table 3-64 gives both the volume and the material for each rolled component.

To calculate the small fuzzy set, the lowest volume, 1.722 in^3 , is divided by each of the other component sizes. The initial membership of the highest volume component is 0.120. The set is normalized by subtracting 0.120 from each of the initial memberships. Table 3-65 gives the normalized memberships for the high cost fuzzy set.

Table 3-64 Volumes and Materials of Rolled Component Set
(Rolled Components)

Component	Material	Length	Volume
1	Aluminum	10.25	1.722 in ³
2	Steel	10.50	1.886 in ³
3	Steel	11.75	2.210 in ³
4	Steel	19.50	2.963 in ³
5	Aluminum	18.50	4.978 in ³
6	Aluminum	26.25	5.371 in ³
7	Steel	44.875	6.510 in ³
8	Steel	49.00	7.232 in ³
9	Aluminum	37.875	11.22 in ³
10	Aluminum	40.25	13.02 in ³

Table 3-65 Normalized Memberships for the Small Fuzzy Set
(Rolled Components)

Component	Material	Length	Volume	Memberships
Minimum			0.000 in ³	1.000
1	Aluminum	10.25	1.722 in ³	0.880
2	Steel	10.50	1.886 in ³	0.793
3	Steel	11.75	2.210 in ³	0.659
4	Steel	19.50	2.963 in ³	0.461
5	Aluminum	18.50	4.978 in ³	0.226
6	Aluminum	26.25	5.371 in ³	0.201
7	Steel	44.875	6.510 in ³	0.145
8	Steel	49.00	7.232 in ³	0.118
9	Aluminum	37.875	11.219 in ³	0.033
10	Aluminum	40.25	13.016 in ³	0.012
Maximum			14.318 in ³	0.000

To calculate the large fuzzy set, 14.318 in^3 , is divided into each of the other component sizes. The initial membership of the lowest volume component is 0.120. The set is normalized by subtracting 0.120 from each of the initial memberships. Table 3-66 gives the normalized memberships for the large fuzzy set.

**Table 3-66 Normalized Memberships for the Large Fuzzy Set
(Rolled Components)**

Component	Material	Length	Volume	Memberships
Minimum			0.000 in^3	0.000
1	Aluminum	10.25	1.722 in^3	0.000
2	Steel	10.50	1.886 in^3	0.012
3	Steel	11.75	2.210 in^3	0.034
4	Steel	19.50	2.963 in^3	0.087
5	Aluminum	18.50	4.978 in^3	0.228
6	Aluminum	26.25	5.371 in^3	0.255
7	Steel	44.875	6.510 in^3	0.335
8	Steel	49.00	7.232 in^3	0.385
9	Aluminum	37.875	11.219 in^3	0.664
10	Aluminum	40.25	13.016 in^3	0.789
Maximum			14.318 in^3	0.880

The medium fuzzy set for each component is determined by subtracting the membership of the small fuzzy set and the membership of the large fuzzy set from 1.0. Table 3-67 gives the memberships of the medium fuzzy set.

**Table 3-67 Memberships in the Medium Fuzzy Set
(Rolled Components)**

Component	Material	Length	Volume	Medium
Minimum			0.000 in ³	0.000
1	Aluminum	10.25	1.722 in ³	0.120
2	Steel	10.50	1.886 in ³	0.197
3	Steel	11.75	2.210 in ³	0.306
4	Steel	19.50	2.963 in ³	0.452
5	Aluminum	18.50	4.978 in ³	0.546
6	Aluminum	26.25	5.371 in ³	0.544
7	Steel	44.875	6.510 in ³	0.521
8	Steel	49.00	7.232 in ³	0.497
9	Aluminum	37.875	11.219 in ³	0.303
10	Aluminum	40.25	13.016 in ³	0.199
Maximum			14.318 in ³	0.120

The complexity of the rolled components is a function of the geometric shape, the primary process and the material. The shape complexity for each component is shown in Table 3-68. The first column under each component contains the geometric dimensions and the second column contains the tolerance on each dimension. The shape complexity is located at the bottom of the first column.

The primary complexity is a function of the length of the component, the processing rate of the rolling mill and the material. The shortest steel component is 10.50 inches long. The shortest aluminum component is 10.25 inches long.

Table 3-68 Shape Complexities for the Rolled Component Set

Component 1		Component 2		Component 3		Component 4		Component 5	
4.00	4.00	3.00	3.00	3.00	3.00	3.000	3.00	3.00	3.00
10.25	0.06	10.50	0.06	11.75	0.06	18.500	0.06	19.50	0.06
1.000	0.06	1.813	0.06	2.125	0.06	2.563	0.06	2.50	0.06
0.750	0.06	0.063	0.03	0.063	0.03	0.063	0.03	0.06	0.03
0.063	0.03								
0.83	0.05	1.06	0.05	1.16	0.05	1.44	0.05	1.45	0.05
15.94		13.25		13.64		14.57		14.61	

Component 6		Component 7		Component 8		Component 9		Component 10	
3.00	3.00	6.00	6.00	6.00	6.00	5.00	5.00	5.00	5.00
26.25	0.06	37.88	0.06	40.25	0.06	44.88	0.06	49.00	0.06
2.75	0.06	2.75	0.06	2.88	0.06	4.00	0.06	4.25	0.06
0.06	0.03	1.06	0.06	1.13	0.06	1.00	0.06	0.94	0.06
		1.44	0.06	0.81	0.06	0.69	0.06	0.44	0.03
		0.94	0.06	0.44	0.03	0.06	0.03	0.06	0.03
		0.06	0.03	0.06	0.03				
1.65	0.05	1.45	0.06	1.19	0.05	1.50	0.05	1.40	0.05
15.17		28.22		27.53		23.95		24.42	

The rolling mill rate for the steel components is:

$$13,680 \text{ inches / hour} = [20 \text{ feet/minute} * 12 \text{ inches/foot} * 57 \text{ minutes / hour}].$$

The rolling mill rate for aluminum components is:

$$27,360 \text{ inches / hour} = [40 \text{ feet/minute} * 12 \text{ inches/foot} * 57 \text{ minutes / hour}].$$

The cost per inch for steel is:

$$\$0.00076 = [10.38 \text{ \$/hour} / 13,680 \text{ inches/hour}].$$

The cost per inch for aluminum is:

$$\$0.00038 = [10.38 \text{ \$/hour} / 27,360 \text{ inches/hour}].$$

The shortest steel component has a cost of:

$$\$0.00797 = [0.00076 \text{ \$/inch} * 10.50 \text{ inches}].$$

The shortest aluminum component has a cost of:

$$\$0.00389 = [0.00038 \text{ \$/inch} * 10.25 \text{ inches}].$$

The primary complexity for each component is calculated by dividing the component's processing cost by the smallest component cost. The smallest component cost is \$0.00389.

The primary complexity of Component 1 is $[(0.00038 * 10.25) / 0.00389] = 1.00$.

The primary complexity of Component 2 is $[(0.00076 * 10.50) / 0.00389] = 2.05$.

The primary complexity of Component 3 is $[(0.00076 * 11.75) / 0.00389] = 2.30$.

The primary complexity of Component 4 is $[(0.00076 * 18.50) / 0.00389] = 3.61$.

The primary complexity of Component 5 is $[(0.00038 * 19.5) / 0.00389] = 1.90$.

The primary complexity of Component 6 is $[0.00038 * 26.25) / 0.00389] = 2.56$.

The primary complexity of Component 7 is $[(0.00076 * 37.875) / 0.00389] = 7.40$.

The primary complexity of Component 8 is $[(0.00076 * 40.25) / 0.00389] = 7.86$.

The primary complexity of Component 9 is $[(0.00038 * 44.875) / 0.00389] = 4.38$.

The primary complexity of Component 10 is $[(0.00038 * 49.00) / 0.00389] = 4.79$.

The secondary complexity is equal to 1.0 for all of the components in the rolled component set. Additional secondary processes are not performed to make the components. As stated in Section 2.0, if a set of components has more than one material, the material complexity is:

$$C_{\text{material}} = \text{LCM} / \text{HMC}$$

Where,

LCM = low cost material

HMC = high cost material

The cost of the steel is \$0.76 and the cost of the aluminum is \$1.137. Thus, steel is the lower cost material.

$$C_{\text{aluminum}} = \$0.76 / \$0.76 = 1.00$$

$$C_{\text{steel}} = \$0.76 / \$1.137 = 0.67$$

The total complexity as defined in Figure 2-1 is:

$$C_{\text{Total}} = C_{\text{Shape}} * C_{\text{P}} * (C_{\text{S1}} * C_{\text{S2}} * \dots * C_{\text{SN}}) * C_{\text{material}}$$

Where

C_{Shape} = geometric shape complexity

C_{P} = complexity contributed by the primary forming processes

$C_{\text{S1}}, C_{\text{S2}}, C_{\text{SN}}$ = complexities contributed by the finishing processes

C_{Material} = complexity contributed by the material

Table 3-69 gives the primary complexities for the rolled component set.

Table 3-69 Primary Complexity of the Rolled Component Set

Component	Length	Material	Process Cost	Primary Complexity
1	10.25	Aluminum	0.004	1.00
2	10.50	Steel	0.008	2.05
3	11.75	Steel	0.009	2.30
4	18.50	Steel	0.014	3.61
5	19.50	Aluminum	0.007	1.90
6	26.25	Aluminum	0.010	2.56
7	37.875	Steel	0.029	7.40
8	40.25	Steel	0.031	7.86
9	44.875	Aluminum	0.017	4.38
10	49.00	Aluminum	0.019	4.79

The total complexity is calculated by multiplying the shape complexity by the primary process complexity and the material complexity.

The total complexity of Component 1 is:

$$15.94[\text{shape}] * 1.00[\text{primary}] * 1.00[\text{material}] = 15.96.$$

The total complexity of Component 2 is:

$$13.25[\text{shape}] * 2.05[\text{primary}] * 0.67[\text{material}] = 18.17.$$

The total complexity of Component 3 is:

$$13.64[\text{shape}] * 2.30[\text{primary}] * 0.67[\text{material}] = 20.93.$$

The total complexity of Component 4 is:

$$14.57[\text{shape}] * 3.61[\text{primary}] * 0.67[\text{material}] = 35.20.$$

The total complexity of Component 5 is:

$$14.61[\text{shape}] * 1.90[\text{primary}] * 1.00[\text{material}] = 27.83.$$

The total complexity of Component 6 is:

$$15.17[\text{shape}] * 2.56[\text{primary}] * 1.00[\text{material}] = 38.90.$$

The total complexity of Component 7 is:

$$28.22[\text{shape}] * 7.40[\text{primary}] * 0.67[\text{material}] = 139.60.$$

The total complexity of Component 8 is:

$$27.53[\text{shape}] * 7.86[\text{primary}] * 0.67[\text{material}] = 144.71.$$

The total complexity of Component 9 is:

$$23.95[\text{shape}] * 4.38[\text{primary}] * 1.0[\text{material}] = 104.99.$$

The total complexity of Component 10 is:

$$24.42[\text{shape}] * 4.79[\text{primary}] * 1.0[\text{material}] = 116.89.$$

The minimum complexity is set to 0.0. The maximum complexity is set to ten percent higher than the highest complexity. Table 3-70 gives the total complexity of the rolled component set.

Table 3-70 Total Complexity of the Rolled Component Set

Component	Length	Material	Shape Complexity	Primary Complexity	Material Complexity	Total Complexity
1	10.25	Aluminum	15.94	1.00	1.00	15.96
2	10.50	Steel	13.25	2.05	0.67	18.17
3	11.75	Steel	13.64	2.30	0.67	20.93
4	18.50	Steel	14.57	3.61	0.67	35.2
5	19.50	Aluminum	14.61	1.90	1.00	27.83
6	26.25	Aluminum	15.17	2.56	1.00	38.90
7	37.875	Steel	28.22	7.40	0.67	139.60
8	40.25	Steel	27.53	7.86	0.67	144.71
9	44.875	Aluminum	23.95	4.38	1.00	104.99
10	49.00	Aluminum	24.42	4.79	1.00	116.89

Dividing the lowest complexity, 15.96, by each of the other complexities, develops the low complexity fuzzy set. This calculation gives the initial membership of each component in the low complexity fuzzy set. Subtracting 0.100 from all the memberships except 0.0 normalizes the set. Table 3-71 gives the normalized memberships in the low complexity fuzzy set.

Table 3-71 Memberships for the Low Complexity Fuzzy Set
(Rolled Components)

Component	Length	Material	Complexity	Memberships
Minimum			0.00	1.000
1	10.25	Aluminum	15.96	0.900
2	10.50	Steel	18.17	0.778
3	11.75	Steel	20.93	0.663
4	18.50	Steel	35.2	0.353
5	19.50	Aluminum	27.83	0.473
6	26.25	Aluminum	38.90	0.310
7	37.875	Steel	139.60	0.014
8	40.25	Steel	144.71	0.010
9	44.875	Aluminum	104.99	0.052
10	49.00	Aluminum	116.89	0.037
Maximum			159.18	0.000

Dividing the maximum complexity, 159.18, into each of the other complexities, develops the high complexity fuzzy set. This calculation gives the initial membership of each component in the high complexity fuzzy set. Subtracting 0.100 from the initial memberships normalizes the set. Table 3-72 gives the normalized memberships in the

high complexity fuzzy set.

The medium complexity fuzzy set for each component is determined by subtracting the membership of the low complexity fuzzy set and the membership of the high complexity fuzzy set from 1.0. Table 3-73 gives the normalized memberships in the medium complexity fuzzy set.

The cost fuzzy sets are determined from the actual cost of the components. The cost of the component is equal to the material cost and the process cost. Table 3-74 gives the total cost of the rolled component set.

Table 3-72 Memberships for the High Complexity Fuzzy Set
(Rolled Components)

Component	Length	Material	Complexity	Memberships
Minimum			0.00	0.000
1	10.25	Aluminum	15.96	0.000
2	10.50	Steel	18.17	0.014
3	11.75	Steel	20.93	0.031
4	18.50	Steel	35.2	0.121
5	19.50	Aluminum	27.83	0.075
6	26.25	Aluminum	38.90	0.144
7	37.875	Steel	139.60	0.777
8	40.25	Steel	144.71	0.809
9	44.875	Aluminum	104.99	0.560
10	49.00	Aluminum	116.89	0.634
Maximum			159.18	0.900

Table 3-73 Memberships in the Medium Complexity Fuzzy Set**(Rolled Components)**

Component	Length	Material	Complexity	Medium
Minimum			0.00	0.000
1	10.25	Aluminum	15.96	0.100
2	10.50	Steel	18.17	0.207
3	11.75	Steel	20.93	0.306
4	18.50	Steel	35.2	0.525
5	19.50	Aluminum	27.83	0.452
6	26.25	Aluminum	38.90	0.545
7	37.875	Steel	139.60	0.209
8	40.25	Steel	144.71	0.181
9	44.875	Aluminum	104.99	0.329
10	49.00	Aluminum	116.89	0.209
Maximum			159.18	0.100

Table 3-74 Total Cost of the Rolled Component Set**(Rolled Components)**

Component	Length	Material	Material Cost	Process Cost	Total Cost
1	10.25	Aluminum	\$0.192	\$0.004	\$0.196
2	10.50	Steel	\$0.406	\$0.008	\$0.414
3	11.75	Steel	\$0.475	\$0.009	\$0.484
4	18.50	Steel	\$0.637	\$0.014	\$0.651
5	19.50	Aluminum	\$0.555	\$0.007	\$0.562
6	26.25	Aluminum	\$0.598	\$0.010	\$0.608
7	37.875	Steel	\$1.400	\$0.029	\$1.429
8	40.25	Steel	\$1.555	\$0.031	\$1.586
9	44.875	Aluminum	\$1.250	\$0.017	\$1.267
10	49.00	Aluminum	\$1.450	\$0.019	\$1.469

Dividing the lowest cost, \$0.196, by each of the other costs, develops the low cost fuzzy set. Subtracting 0.108 from all the memberships except zero normalizes the set. Table 3-75 gives the memberships for the low cost fuzzy set.

Table 3-75 Memberships for the Low Cost Fuzzy Set
(Rolled Components)

Component	Length	Material	Cost	Memberships
Minimum			\$0.000	1.000
1	10.25	Aluminum	\$0.196	0.892
2	10.50	Steel	\$0.414	0.365
3	11.75	Steel	\$0.484	0.296
4	18.50	Steel	\$0.651	0.193
5	19.50	Aluminum	\$0.562	0.240
6	26.25	Aluminum	\$0.608	0.214
7	37.875	Steel	\$1.429	0.029
8	40.25	Steel	\$1.586	0.015
9	44.875	Aluminum	\$1.267	0.046
10	49.00	Aluminum	\$1.469	0.025
Maximum			\$1.821	0.000

Dividing the maximum cost, \$1.821, into each of the other component costs, develops the high cost fuzzy set. Subtracting 0.108 from all the initial memberships except zero normalizes the set. Table 3-76 gives the memberships for the high cost fuzzy set.

Table 3-76 Memberships in the High Cost Fuzzy Set
(Rolled Components)

Component	Length	Material	Cost	Memberships
Minimum			\$0.000	0.000
1	10.25	Aluminum	\$0.196	0.000
2	10.50	Steel	\$0.414	0.119
3	11.75	Steel	\$0.484	0.158
4	18.50	Steel	\$0.651	0.250
5	19.50	Aluminum	\$0.562	0.201
6	26.25	Aluminum	\$0.608	0.226
7	37.875	Steel	\$1.429	0.677
8	40.25	Steel	\$1.586	0.763
9	44.875	Aluminum	\$1.267	0.588
10	49.00	Aluminum	\$1.469	0.699
Maximum			\$1.821	0.892

The medium cost fuzzy set for each component is determined by subtracting the membership of the low cost fuzzy set and the membership of the high cost fuzzy set from

1.0. Table 3-77 gives the memberships for the medium cost fuzzy set.

Table 3-77 Memberships in the Medium Cost Fuzzy Set

(Rolled Components)				
Component	Length	Material	Cost	Medium
Minimum			\$0.000	0.000
1	10.25	Aluminum	\$0.196	0.108
2	10.50	Steel	\$0.414	0.516
3	11.75	Steel	\$0.484	0.546
4	18.50	Steel	\$0.651	0.558
5	19.50	Aluminum	\$0.562	0.559
6	26.25	Aluminum	\$0.608	0.560
7	37.875	Steel	\$1.429	0.294
8	40.25	Steel	\$1.586	0.222
9	44.875	Aluminum	\$1.267	0.366
10	49.00	Aluminum	\$1.469	0.276
Maximum			\$1.821	0.108

3.3 Estimating the Cost

To estimate the cost of a component the fuzzy cost sets are defuzzified. Defuzzification decodes the fuzzy cost set information produced by the fuzzy rules. The defuzzification method calculates a crisp cost for a component. There are various types of defuzzification methods available to decode fuzzy set information. However, for this research, the center of gravity method, a common method used to defuzzify fuzzy controllers [15] is used.

To illustrate how the center of gravity method is used consider the triangular functions shown in Figure 3-1. These triangular functions represent three fuzzy cost sets i.e. low, medium and high. The center of gravity of each triangle is located at the center of the triangle, $(c_i + b_i)/2$, as shown in Figure 3-1. The center of gravity is \$0.125 for the low cost fuzzy set, \$0.175 for the medium cost fuzzy set and \$0.225 for the high cost fuzzy set. The area of all three triangles is equal to the base times the height or $A = \frac{1}{2} * b_i * h$. The height is equal to 1.0 and the base is equal to \$0.15. The area of each triangle is equal to \$0.075. The contribution of a fuzzy cost function is calculated by multiplying the center of gravity ($C_{gravity}$) by the area. Thus, the contribution of the low cost fuzzy function is:

$$C_{low} = \$0.125 * \$0.075$$

$$C_{low} = \$\$0.0094$$

The contribution of the medium cost fuzzy function is:

$$C_{\text{medium}} = \$0.175 * \$0.075$$

$$C_{\text{medium}} = \$\$0.0131$$

The contribution of the high cost fuzzy function is:

$$C_{\text{high}} = \$0.225 * \$0.075$$

$$C_{\text{high}} = \$\$0.0169$$

The crisp cost is calculated by summing the contributions made by each fuzzy cost function and dividing the sum of the contributions by the sum of the areas.

$$C_{\text{crisp}} = [C_{\text{low}} + C_{\text{medium}} + C_{\text{high}}] / [A_{\text{low}} + A_{\text{medium}} + A_{\text{high}}]$$

$$C_{\text{crisp}} = [\$\$0.0094 + \$\$0.0131 + \$\$0.0169] / [\$0.075 + \$0.075 + \$0.075]$$

$$C_{\text{crisp}} = [\$\$0.0394 / \$0.225]$$

$$C_{\text{crisp}} = \$0.175$$

This is the center of the medium cost function.

Figure 3-1 Triangular Cost Functions

When the triangular functions are “cutoff”, the triangular functions become trapezoidal functions as shown in Figure 3-2. The fuzzy cost sets are “cutoff” at the memberships determined from the fuzzy logic rules. The area of a trapezoid is equal to the average of the base plus the distance between the “cutoff” points times the height or $A = (b_i + a_i)/2 * h$. However, the center of gravity is still located at the same point either, $(c_i + b_i)/2$ or $[P_i + P_{i+1}]/2$

To illustrate, suppose the fuzzy rules give a “cutoff” membership of 0.45 for the low cost fuzzy set, a “cutoff” membership of 0.35 for the medium cost fuzzy set and a “cutoff” membership of 0.20 for the high cost fuzzy set. The center of gravity of a trapezoid is

$$C_{\text{gravity}} = (P_i + P_{i+1}) / 2$$

Where, P_i is the first point at the “cutoff” membership

P_{i+1} is the second point at the “cutoff” membership

The points for each cost set are found from the following equations where b_i is the cost difference at a membership of zero and h_i is the “cutoff” membership.

$$P_1 = c_1 + [b_1 / 2] * h_1$$

$$P_2 = c_4 - [b_1 / 2] * h_1$$

$$P_3 = c_2 + [b_2 / 2] * h_2$$

$$P_4 = c_5 - [b_2 / 2] * h_2$$

$$P_5 = c_3 + [b_3 / 2] * h_3$$

$$P_6 = c_6 - [b_3 / 2] * h_3$$

Figure 3-2 Trapezoid Cost Functions

The equations for P_i and P_{i+1} are linear. For example, at a zero membership P_1 is equal to c_1 . At a membership of one, P_1 is equal to $c_1 + [b_1 / 2]$. Thus, the equation for P_1 is:

$$c_1 + [b_1 / 2] * h_1$$

The center of gravity for the low cost trapezoid is:

$$C_{\text{gravity low}} = (P_1 + P_2) / 2$$

$$P_1 = c_1 + [b_1 / 2] * h_1$$

Where

$$b_1 = \$0.20 - \$0.05 = \$0.15$$

$$c_1 = \$0.05$$

$$h_1 = 0.45$$

$$P_1 = \$0.05 + [\$0.15 / 2] * 0.45$$

$$P_1 = \$0.084$$

$$P_2 = c_4 - [b_1 / 2] * h_1$$

Where

$$c_4 = \$0.20$$

$$P_2 = \$0.20 - [\$0.15 / 2] * 0.45$$

$$P_2 = \$0.166$$

$$C_{\text{gravity low}} = (\$0.166 + \$0.084) / 2 = \$0.125$$

The center of gravity for the medium cost trapezoid is

$$C_{\text{gravity low}} = (P_3 + P_4) / 2$$

$$P_3 = c_2 + [b_2 / 2] * h_2$$

Where

$$b_2 = \$0.25 - \$0.10 = \$0.15$$

$$c_1 = \$0.10$$

$$h_1 = 0.35$$

$$P_3 = \$0.10 + [\$0.15 / 2] * 0.35$$

$$P_3 = \$0.126$$

$$P_5 = c_5 - [b_2 / 2] * h_2$$

Where

$$c_5 = \$0.25$$

$$P_5 = \$0.25 - [\$0.15 / 2] * 0.35$$

$$P_5 = \$0.224$$

$$C_{\text{gravity medium}} = (\$0.126 + \$0.224) / 2 = \$0.175$$

The center of gravity for the high cost trapezoid is

$$C_{\text{gravity high}} = (P_5 + P_6) / 2$$

$$P_5 = c_3 + [b_3 / 2] * h_3$$

Where

$$b_3 = \$0.30 - \$0.15 = \$0.15$$

$$c_3 = \$0.15$$

$$h_1 = 0.20$$

$$P_5 = \$0.15 + [\$0.15 / 2] * 0.20$$

$$P_5 = \$0.165$$

$$P_6 = c_6 - [b_3 / 2] * h_3$$

Where

$$c_6 = \$0.30$$

$$P_6 = \$0.30 - [\$0.15 / 2] * 0.20$$

$$P_6 = \$0.285$$

$$C_{\text{gravity high}} = (\$0.165 + \$0.285) / 2 = \$0.225$$

The area of a trapezoid is equal to:

$$A = h_i / 2 * [a_i + b_i]$$

Where

A is the area of the trapezoid

b_i is the cost difference at a membership of zero.

h_i is the “cutoff” membership

a_i is the cost difference at the “cutoff” membership

The cost difference, a_i , is $P_2 - P_1$ for the low cost fuzzy set, $P_4 - P_3$ for the medium cost fuzzy set and $P_6 - P_5$ for the high cost fuzzy set. P_1, P_2, P_3, P_4, P_5 and P_6 are the costs at the “cutoff” memberships.

The area of the low cost trapezoid is

$$A_{\text{Low}} = h_1 / 2 * [a_1 + b_1]$$

$$b_1 = \$0.20 - \$0.05 = \$0.15$$

$$h_1 = 0.45$$

$$a_1 = P_2 - P_1 = \$0.166 - \$0.084 = \$0.082$$

$$P_1 = c_1 + [b_1 / 2] * h_1$$

$$P_1 = \$0.05 + [\$0.15 / 2] * 0.45$$

$$P_1 = \$0.084$$

$$P_2 = c_4 - [b_1 / 2] * h_1$$

$$P_2 = \$0.20 - [\$0.15 / 2] * 0.45$$

$$P_2 = \$0.166$$

$$A_{\text{Low}} = h_1 / 2 * [a_1 + b_1]$$

$$A_{\text{Low}} = 0.45 / 2 * [\$0.082 + \$0.15]$$

$$A_{\text{Low}} = \$0.052$$

The area of the medium cost trapezoid is

$$A_{\text{medium}} = h_2 / 2 * [a_2 + b_2]$$

$$b_2 = \$0.25 - \$0.10 = \$0.15$$

$$h_2 = 0.35$$

$$a_2 = P_4 - P_3 = \$0.224 - \$0.126 = \$0.098$$

$$P_3 = c_2 + [b_2 / 2] * h_2$$

$$P_3 = \$0.10 + [\$0.15 / 2] * 0.35$$

$$P_3 = \$0.126$$

$$P_4 = c_5 - [b_2 / 2] * h_2$$

$$P_4 = \$0.25 - [\$0.15 / 2] * 0.35$$

$$P_4 = \$0.224$$

$$A_{\text{Medium}} = h_2 / 2 * [a_2 + b_2]$$

$$A_{\text{Medium}} = 0.35 / 2 * [\$0.098 + \$0.15]$$

$$A_{\text{Medium}} = \$0.043$$

The area of the high cost trapezoid is

$$A_{\text{high}} = h_3 / 2 * [a_3 + b_3]$$

$$b_3 = \$0.30 - \$0.15 = \$0.15$$

$$h_3 = 0.20$$

$$a_3 = P_6 - P_5 = \$0.285 - \$0.165 = \$0.120$$

$$P_5 = c_3 + [b_3 / 2] * h_3$$

$$P_5 = \$0.15 + [\$0.15 / 2] * 0.20$$

$$P_5 = \$0.165$$

$$P_6 = c_6 - [b_3 / 2] * h_3$$

$$P_6 = \$0.30 - [\$0.15 / 2] * 0.20$$

$$P_6 = \$0.285$$

$$A_{\text{high}} = h_3 / 2 * [a_3 + b_3]$$

$$A_{\text{high}} = 0.20 / 2 * [\$0.120 + \$0.15]$$

$$A_{\text{high}} = \$0.027$$

The contribution from the low cost fuzzy set is

$$C_{\text{Low}} = C_{\text{gravity low}} * A_{\text{Low}}$$

$$C_{\text{Low}} = \$0.125 * \$0.052$$

$$C_{\text{Low}} = \$0.007$$

The contribution from the medium cost fuzzy set is

$$C_{\text{Medium}} = C_{\text{gravity medium}} * A_{\text{medium}}$$

$$C_{\text{Medium}} = \$0.175 * \$0.043$$

$$C_{\text{Medium}} = \$0.008$$

The contribution from the high cost fuzzy set is

$$C_{\text{high}} = C_{\text{gravity high}} * A_{\text{high}}$$

$$C_{\text{high}} = \$0.225 * \$0.027$$

$$C_{\text{high}} = \$0.006$$

The crisp cost is equal to

$$C_{\text{crisp}} = [C_{\text{low}} + C_{\text{medium}} + C_{\text{high}}] / [A_{\text{low}} + A_{\text{medium}} + A_{\text{high}}]$$

$$C_{\text{crisp}} = [\$0.007 + \$0.008 + \$0.006] / [\$0.052 + \$0.043 + \$0.027]$$

$$C_{\text{crisp}} = [\$0.021 / \$0.122]$$

$$C_{\text{crisp}} = \$0.172$$

The crisp cost is shown in Figure 3-2.

The fuzzy cost functions for the stamped, injection molded, rolled and extruded component sets are triangular and trapezoidal. The low cost and high cost functions are triangular. The medium cost function is trapezoidal. For example, consider the cost fuzzy sets for the stamped components shown in Figure 3-3. Figure 3-3 is developed by plotting the memberships against the cost at that membership. The memberships and costs for the low cost fuzzy set are taken from Table 3-19. The memberships and costs for the medium cost fuzzy set are taken from Table 3-22. The memberships and costs for the high cost fuzzy set are taken from Table 3-21.

Figure 3-3 Cost Fuzzy Sets for the Stamped Component Set

The fuzzy size and complexity functions for the stamped, injection molded, rolled and extruded component sets are also triangular and trapezoidal. Figure 3-4 shows the size functions for the stamped component set. Figure 3-5 shows the complexity functions for the stamped component set.

Figure 3-4 Size Fuzzy Sets for the Stamped Component Set

Figure 3-5 Complexity Fuzzy Sets for the Stamped Component Set

The cost functions for a stamped component are used to illustrate how a crisp cost is calculated. Figure 3-6 shows the cutoff points for Component 10's cost functions. The cost functions are determined from the fuzzy rules. The size of Component 10 is 0.883 in³ and the complexity is 132. The min-max inference procedure is applied to find the "cutoff" memberships for the component. The rules are:

Rule 1: If the complexity of Component 10 is low and the size of Component 10 is low then the cost of Component 10 is low. The membership of 132 in the low complexity set is 0.105 (Table 3-13). The membership of 0.883 in³ in the low size set is 0.012 (Table 3-4). The memberships may also be obtained from Figures 3-5 and 3-4.

$$\text{Min } [0.105, 0.012] = 0.012$$

Rule 2: If the complexity of Component 10 is low and the size of Component 10 is medium then the cost of Component 10 is low. The membership of 132 in the low complexity set is 0.105 (Table 3-13). The membership of 0.883 in³ in the medium size set is 0.203 (Table 3-4). The memberships may also be obtained from Figures 3-5 and 3-4.

$$\text{Min } [0.105, 0.203] = 0.105$$

Rule 3: If the complexity of Component 10 is low and the size of Component 10 is high then the cost of Component 10 is medium. The membership of 132 in the low complexity set is 0.105 (Table 3-13). The membership of 0.883 in³ in the high size set is 0.784 (Table 3-4). The memberships may also be obtained from Figures 3-5 and 3-4.

$$\text{Min } [0.105, 0.784] = 0.105$$

Rule 4: If the complexity of Component 10 is medium and the size of Component 10 is low then the cost of Component 10 is low. The membership of 132 in the medium complexity set is 0.616 (Table 3-13). The membership of 0.883 in³ in the low size set is 0.012 (Table 3-4). The memberships may also be obtained from Figures 3-5 and 3-4.

$$\text{Min } [0.616, 0.012] = 0.012$$

Rule 5: If the complexity of Component 10 is medium and the size of Component 10 is medium then the cost of Component 10 is medium. The membership of 132 in the medium complexity set is 0.616 (Table 3-13). The membership of 0.883 in³ in the medium size set is 0.204 (Table 3-4). The memberships may also be obtained from Figures 3-5 and 3-4.

$$\text{Min } [0.616, 0.203] = 0.203$$

Rule 6: If the complexity of Component 10 is medium and the size of Component 10 is high then the cost of Component 10 is high. The membership of 132 in the medium complexity set is 0.616 (3-13). The membership of 0.883 in³ in the high size set is 0.783 (Table 3-4). The memberships may also be obtained from Figures 3.3-5 and 3-4.

$$\text{Min } [0.616, 0.783] = 0.616$$

Rule 7: If the complexity of Component 10 is high and the size of Component 10 is low then the cost of Component 10 is medium. The membership of 132 in the high complexity set is 0.279 (Table 3-13). The membership of 0.883 in³ in the low size set is 0.012 (Table 3-4). The memberships may also be obtained from Figures 3.3-5 and 3.3-4.

$$\text{Min } [0.279, 0.012] = 0.012$$

Rule 8: If the complexity of Component 10 is high and the size of Component 10 is medium then the cost of Component 10 is high. The membership of 132 in the high complexity set is 0.279 (Table 3-13). The membership of 0.883 in³ in the medium size set is 0.203 (Table 3-4). The memberships may also be obtained from Figures 3-5 and 3-4.

$$\text{Min } [0.279, 0.203] = 0.203$$

Rule 9: If the complexity of Component 10 is high and the size of Component 10 is high then the cost of Component 10 is high. The membership of 132 in the high complexity set is 0.279 (Table 3-13). The membership of 0.883 in³ in the high size set is 0.784 (Table 3-4). The memberships may also be obtained from Figures 3-5 and 3-4.

$$\text{Min } [0.279, 0.784] = 0.279$$

Once the minimum membership is obtained for each rule, the next step is to obtain the maximum membership of Component 10 in each fuzzy cost set. For the low cost fuzzy set, there are three memberships.

From Rule 1: membership = 0.012

From Rule 2: membership = 0.105

From Rule 4: membership = 0.012

The amount of membership in the low cost fuzzy set is the maximum of the three memberships. This is the “cutoff” membership for the low cost fuzzy set.

$$\text{Max } [0.012, 0.105, 0.012] = 0.105$$

For the medium cost fuzzy set there are three memberships represented:

From Rule 3: membership = 0.105

From Rule 5: membership = 0.203

From Rule 7: membership = 0.012

The amount of membership in the medium cost fuzzy set is the maximum of the three memberships. This is the “cutoff” membership of the medium cost fuzzy set.

$$\text{Max } [0.105, 0.203, 0.012] = 0.203$$

For the high cost fuzzy set there are three memberships represented.

From Rule 6: membership = 0.616

From Rule 8: membership = 0.203

From Rule 9: membership = 0.279

The amount of membership in the high cost fuzzy set is the maximum of the three memberships. This is the “cutoff” membership for the high cost fuzzy set.

$$\text{Max } [0.616, 0.203, 0.279] = 0.616$$

The cost for Component 10 is calculated as follows.

The center of gravity for the low cost fuzzy set is:

$$C_{\text{gravity low}} = \frac{[P_2^2 * 0.5] + [[P_2 + [(P_7 - P_2) * 1/3] * 0.5] * (P_7 - P_2)]}{[P_2 + (P_7 - P_2) * 0.5]}$$

To find P_2 , a linear interpolation is performed at the “cutoff” membership. In this case, from Table 3-14, the cost at a membership of 0.105 is between \$0.117 and \$0.170. At \$0.117, the membership is 0.186. At 0.170, the membership is 0.079.

Figure 3-6 Component 10 Cutoff Cost Functions

The formula used to calculate the cost is:

$$C_{\text{cutoff}} = C_A - [(C_A - C_B) / (M_A - M_B) * (M_A - M_{\text{cutoff}})]$$

Where

C_A is the cost above the “cutoff” membership

C_B is the cost below the “cutoff” membership

M_A is the membership above the “cutoff” membership

M_B is the membership below the “cutoff” membership

M_{cutoff} is the “cutoff” membership

$$C_{\text{cutoff}} = \$0.170 - [(\$0.170 - \$0.117) / (0.079 - 0.186) * (0.079 - 0.105)]$$

$$C_{\text{cutoff}} = \$0.157$$

$$P_2 = \$0.157$$

$$P_7 = \$0.232$$

$$C_{\text{gravity low}} = \frac{[\$0.157^2 * 0.5] + [\$0.157 + [\$0.232 - \$0.157] * 1/3] * 0.5 * [\$0.232 - \$0.157]}{[\$0.157 + [\$0.232 - \$0.157] * 0.5]}$$

$$C_{\text{gravity low}} = \$0.099$$

The center of gravity for the medium cost fuzzy set is:

$$C_{\text{gravity medium}} = (P_3 + P_4) / 2$$

To find P_3 & P_4 , linear interpolations are performed at the “cutoff” membership. For P_3 , the cost at a membership of 0.203 is between \$0.047 and \$0.041. This is from Table 3-14. At \$0.047, the membership is 0.263. At 0.041, the membership is 0.145. The formula used to calculate the cost is:

$$C_{\text{cutoff}} = C_A - [(C_A - C_B) / (M_A - M_B) * (M_A - M_{\text{cutoff}})]$$

$$C_{\text{cutoff}} = \$0.047 - [(\$0.047 - \$0.040) / (0.276 - 0.159) * (0.276 - 0.203)]$$

$$C_{\text{cutoff}} = \$0.043$$

$$P_3 = C_{\text{cutoff}}$$

$$P_3 = \$0.043$$

For P_4 , the cost at a membership of 0.203 is between \$0.255 and \$0.232. This is from Table 3-14. At \$0.255, the membership is 0.159. At 0.232, the membership is 0.233. The formula used to calculate the cost is:

$$C_{\text{cutoff}} = C_A - [(C_A - C_B) / (M_A - M_B) * (M_A - M_{\text{cutoff}})]$$

$$C_{\text{cutoff}} = \$0.255 - [(\$0.255 - \$0.232) / (0.159 - 0.233) * (0.145 - 0.203)]$$

$$C_{\text{cutoff}} = \$0.241$$

$$P_4 = C_{\text{cutoff}}$$

$$P_4 = \$0.241$$

$$C_{\text{gravity medium}} = (\$0.241 + \$0.043) / 2$$

$$C_{\text{gravity medium}} = \$0.142$$

The center of gravity for the high cost fuzzy set is:

$$C_{\text{gravity high}} = \frac{[(P_6 - P_5) * (P_6 + P_5) / 2] + [(P_3 + [(P_5 - P_3) * 2 / 3] / 2 * (P_5 - P_3))]}{[(P_6 - P_5) + (P_5 - P_3) * 0.5]}$$

$$P_6 = \$0.255 \text{ (maximum cost)}$$

To find P_5 , a linear interpolation is performed at the “cutoff” membership. For P_5 , the cost at a membership of 0.616 is between \$0.211 and \$0.170. This is from Table 3-14. At \$0.211, the membership is 0.667. At 0.170, the membership is 0.509. The formula used to calculate the cost is:

$$C_{\text{cutoff}} = C_A - [(C_A - C_B) / (M_A - M_B) * (M_A - M_{\text{cutoff}})]$$

$$C_{\text{cutoff}} = \$0.211 - [(\$0.211 - \$0.170) / (0.667 - 0.509) * (0.667 - 0.616)]$$

$$C_{\text{cutoff}} = \$0.198$$

$$P_5 = \$0.198$$

$$C_{\text{gravity high}} = \frac{[(\$0.26 - \$0.20) * (\$0.26 + \$0.20) / 2] + [\$0.04 + [(\$0.20 - \$0.04) * 2 / 3] / 2 * (\$0.20 - \$0.04)]}{[(\$0.26 - \$0.20) + (\$0.20 - \$0.04) * 0.5]}$$

$$C_{\text{gravity high}} = \$0.18$$

The area of the low cost fuzzy set is found by dividing the area under the curve into a rectangle and a right triangle. The area of the rectangle is $(P_2 * h_1)$. The area of the right triangle is $(\frac{1}{2} * (P_6 - P_2) * h_1)$. Thus the area for the low cost fuzzy set is:

$$A_{\text{low}} = (P_2 * h_1) + (\frac{1}{2} * (P_6 - P_2) * h_1)$$

$$P_2 = 0.157 \text{ (calculated above)}$$

$$P_6 = 0.255 \text{ (maximum cost)}$$

$$h_1 = 0.105 \text{ (maximum "cutoff" for the low cost fuzzy set)}$$

$$A_{\text{low}} = (0.157 * 0.105) + (1/2 * (0.255 - 0.157) * 0.105)$$

$$A_{\text{low}} = \$0.0204$$

The area of the medium cost fuzzy set is found for a trapezoid:

$$A_{\text{medium}} = h_2 * ((P_4 - P_3) + P_6) / 2$$

$$P_3 = \$0.043 \text{ (calculated above)}$$

$$P_4 = \$0.241 \text{ (calculated above)}$$

$$P_6 = \$0.255 \text{ (maximum cost)}$$

$$h_2 = 0.203 \text{ (maximum "cutoff" for the medium cost fuzzy set)}$$

$$A_{\text{medium}} = 0.203 * ((\$0.241 - \$0.043) + \$0.255) / 2$$

$$A_{\text{medium}} = \$0.0463$$

The area of the high cost fuzzy set is found by dividing the area under the curve into a rectangle and a right triangle. The area of the rectangle is $((P_6 - P_5) * h_3)$. The area of the right triangle is $(\frac{1}{2} * P_5 * h_3)$. Thus, the area for the high cost fuzzy set is:

$$A_{\text{high}} = ((P_6 - P_5) * h_3) + (\frac{1}{2} * P_5 * h_3)$$

$$P_5 = 0.198 \text{ (calculated above)}$$

$$P_6 = 0.255 \text{ (maximum cost)}$$

$$h_3 = 0.616 \text{ (maximum "cutoff" for the high cost fuzzy set)}$$

$$A_{\text{high}} = ((\$0.255 - 0.198) * 0.616) + (1/2 * 0.198 * 0.616)$$

$$A_{\text{high}} = \$0.083$$

The contribution from the low cost fuzzy set is

$$C_{\text{Low}} = C_{\text{gravity low}} * A_{\text{Low}}$$

$$C_{\text{Low}} = \$0.099 * \$0.0204$$

$$C_{\text{Low}} = \$\$0.0020$$

The contribution from the medium cost fuzzy set is

$$C_{\text{Medium}} = C_{\text{gravity medium}} * A_{\text{medium}}$$

$$C_{\text{Medium}} = \$0.142 * \$0.0463$$

$$C_{\text{Medium}} = \$\$0.0066$$

The contribution from the high cost fuzzy set is

$$C_{\text{high}} = C_{\text{gravity high}} * A_{\text{high}}$$

$$C_{\text{high}} = \$0.180 * \$0.083$$

$$C_{\text{high}} = \$0.0150$$

The crisp cost is equal to

$$C_{\text{crisp}} = [C_{\text{low}} + C_{\text{medium}} + C_{\text{high}}] / [A_{\text{low}} + A_{\text{medium}} + A_{\text{high}}]$$

$$C_{\text{crisp}} = [\$0.0020 + \$0.0066 + \$0.0150] / [\$0.0204 + \$0.0463 + \$0.0830]$$

$$C_{\text{crisp}} = [\$0.0235 / \$0.1496]$$

$$C_{\text{crisp}} = \$0.157$$

The actual cost of Component 10 is \$0.2321. Thus, the estimated cost is approximately 32 % less than the actual cost.

4.0 Application of the Fuzzy Logic Cost Estimation Method

The fuzzy logic cost estimation method is developed into a cost-estimating tool by modeling the method in an Excel spreadsheet. A separate sheet is used for each component set and the model is setup the same way in each spreadsheet. Tables 4.1, 4.2, 4.3, 4.4 and 4.5 show the models for stamped components, small injection molded components, large injection molded components, rolled components and extruded components, respectively.

The size or volume fuzzy sets are shown at the top of the sheet. The memberships for the fuzzy set are shown in a table labeled volume, small, medium and large. A space is available beside the volume fuzzy set table to input a volume and a complexity for the component to be evaluated. Two logic tables with logic equations are located directly below the volume fuzzy sets. These logic tables are used to find the volumes and memberships that are below and above the input volume. The volumes and memberships selected are used to find the membership of the input volume in each fuzzy set. A linear regression analysis is performed to find the membership.

The complexity fuzzy sets are located directly below the logic tables for the volume fuzzy sets. The memberships for the fuzzy set are shown in a table labeled complexity, low, medium and high. The complexities that make up the total complexity are shown beside the complexity table. The shape complexity, primary complexity and secondary complexity are shown for the stamped component model. The shape complexity and primary complexity are shown for the injection-molded components. The shape complexity, primary complexity and the material complexity are shown for the extruded and rolled components. For the extruded and rolled components, the length and material are also provided. Two Logic tables with logic equations are located directly below the complexity fuzzy sets. These logic tables are used to find the complexities and memberships that are below and above the input complexity. The complexities and memberships selected are used to find the membership of the input complexities in each fuzzy set. A linear regression analysis is performed to find the membership.

The cost fuzzy sets are located directly below the logic tables for the complexity fuzzy sets. The memberships for the fuzzy set are shown in a table labeled cost, low, medium and high. The material cost and processing cost are shown beside of the cost table.

The fuzzy rules for the model are located in a table directly below the cost table. The fuzzy rule table shows the “cutoff” membership selected for each of the rules. The table also shows the “cutoff” membership selected for each of the cost fuzzy sets.

The logic table for the cost fuzzy sets is located below the fuzzy rule table. The logic equations find the cost and memberships below or above the “cutoff” membership calculated in the fuzzy rule table. Equations to calculate the cost at the “cutoff” membership are located below the logic equations.

The cost is estimated using the methodology described in Section 3.3. The estimated cost table is located below the cost logic table. This table uses the “cutoff” costs and memberships to calculate the estimated cost. The table shows, in order, the contribution of the low cost fuzzy set, the contribution of the medium cost fuzzy set and the high cost fuzzy set. Directly below the contribution are the area of the low cost fuzzy set, the medium cost fuzzy set and the high cost fuzzy set.

To illustrate how the fuzzy logic model works consider the example shown in Table 4-5 for the extruded components. A volume of 0.556 in^3 is the input volume. A complexity of 20.5 is the input complexity.

As stated above, the first set of logic equations select the volume and associated memberships that are lower or equal to the input. These equations compare the input number, INPUT, to the volumes in the table. There are two conditions to be met before the logic equation is true. For example, when INPUT is compared to Volume 1 and Volume 2, the first condition is $\text{INPUT} \geq \text{Volume 1}$. The second condition is $\text{INPUT} < \text{Volume 2}$. If both conditions are true, i.e. INPUT is either equal to or between the two volumes, then Volume 1 is selected as the lower volume. If both conditions are false or only one condition is true, then neither volume is selected. In the model, a 0.0 is entered if the conditions are not true. The EXCEL formula is:

IF [(INPUT $\geq$ Volume 1, INPUT $<$ Volume 2), Volume 1, 0.0].

Thus, when the input volume of 0.556 is compared to Volume 1 = 0.0 and Volume 2 = 0.556, the first condition is true and the second condition is false. Thus, a zero is entered in the logic table.

IF [(0.556 $\geq$ 0.0, 0.556 $<$ 0.556), 0.0, 0.0]

The next equation in the logic table compares 0.556 to Volume 2 = 0.556 and Volume 3 = 1.355. For this equation, the first condition is true and the second condition is true. Thus, 0.556 is entered in the logic table.

IF [(0.556 $\geq$ 0.556, 0.556 $<$ 1.355), 0.556, 0.0]

For all the other equations in the table, the conditions are false and a 0.0 is entered. Memberships are selected when the volume is selected and are entered in the table when the volume conditions are both true.

The second set of logic equations in the volume logic table select the volume above the input volume. The EXCEL formula is:

IF [(INPUT <= Volume 1, INPUT < Volume 2), Volume 1=0.0]

Thus, when the input volume of 0.556 is compared to Volume 1 = 0.0 and Volume 2 = 0.556, the first condition is false and the second condition is false. Thus, a zero is entered in the logic table.

IF [(0.556 <= 0.0, 0.556 < 0.556), 0.0, 0.0]

The next equation in the logic table compares 0.556 to Volume 2 = 0.556 and Volume 3 = 1.355. For this equation, the first condition is true and the second condition is true. However, this time 1.355 is entered into the logic table because it is the higher volume. Again, the memberships associated with the volume of 1.355 are entered in the logic table.

IF [(0.556 <= 0.556, 0.556 < 1.355), 1.355, 0.0]

Once the volumes and the associated memberships are selected, a linear regression

calculation is used to determine the membership of the input volume in each set. First the average volume and the average membership for each fuzzy set is calculated.

The average volume is $[(0.556 + 1.355) / 2] = 0.956$.

The average membership in the small fuzzy set is $[(0.929 + 0.339) / 2] = 0.634$.

The average membership in the medium fuzzy set is $[(0.071 + 0.559) / 2] = 0.315$.

The average membership in the large fuzzy set is $[(0.000 + 0.102) / 2] = 0.051$.

The next step is to calculate the estimated regression equation for each membership set.

The form of the estimated regression equation is:

$$y = b_o + (b_1 * x_{avg}).$$

$$b_1 = \sum ((x_1 - x_{avg}) * (y_1 - y_{avg})) / \sum (x_1 - x_{avg})^2$$

$$b_o = y_{avg} - (b_1 * x_{avg}).$$

For the small fuzzy set:

$$x_1 = 0.544$$

$$x_2 = 1.355$$

$$y_1 = 0.929$$

$$y_2 = 0.339$$

$$x_{avg} = 0.956$$

$$y_{\text{avg}} = 0.634$$

$$b_1 = \frac{((0.544-0.956) + (1.355-0.956)) * ((0.929-0.634) + (0.339-0.634))}{(0.544 - 0.929)^2 + (0.544 - 0.929)^2}$$

$$b_1 = -0.738$$

$$b_o = 0.634 - (-0.738) * (0.956)$$

$$b_o = 1.339$$

$$y = 1.339 - (0.738 * \text{INPUT})$$

$$y = 1.339 - (0.738 * 0.556)$$

$$y = 0.929 \text{ (membership of 0.556 in the small fuzzy set)}$$

For the medium fuzzy set:

$$x_1 = 0.544$$

$$x_2 = 1.355$$

$$y_1 = 0.071$$

$$y_2 = 0.559$$

$$x_{\text{avg}} = 0.956$$

$$y_{\text{avg}} = 0.315$$

$$b_1 = 0.610$$

$$b_o = -0.268$$

$$y = -0.268 + (0.610 * \text{INPUT})$$

$$y = -0.268 + (0.610 * 0.556)$$

$$y = 0.071 \text{ (membership of 0.556 in the medium fuzzy set)}$$

For the large fuzzy set:

$$x_1 = 0.544$$

$$x_2 = 1.355$$

$$y_1 = 0.000$$

$$y_2 = 0.102$$

$$x_{\text{avg}} = 0.956$$

$$y_{\text{avg}} = 0.051$$

$$b_1 = 0.128$$

$$b_o = -0.071$$

$$y = -0.071 + (0.128 * \text{INPUT})$$

$$y = -0.071 + (0.128 * 0.556)$$

$$y = 0.000 \text{ (membership of 0.556 in the large fuzzy set)}$$

For the input complexity the same type of calculations are performed to determine the membership of the complexity in each complexity fuzzy set. The first set of logic equations select the complexity and associated memberships that are lower or equal to the input. These equations compare the input number, INPUT, to the complexities in the

table. There are two conditions to be met before the logic equation is true. For example, when INPUT is compared to Complexity 1 and Complexity 2, the first condition is $INPUT \geq \text{Complexity 1}$. The second condition is $INPUT < \text{Complexity 2}$. If both conditions are true, i.e. INPUT is either equal to or between the two complexities, then Complexity 1 is selected as the lower complexity. If both conditions are false or only one condition is true, then neither complexity is selected. In the model, a 0.0 is entered if the conditions are not true. The EXCEL formula is:

IF [(INPUT $\geq$ Complexity 1, INPUT $<$ Complexity 2), Complexity 1, 0.0]

Thus, when the input complexity of 20.5 is compared to Complexity 1 = 0.0 and Complexity 2 = 20.5, the first condition is true and the second condition is false. Thus, a zero is entered in the logic table.

IF [(20.5 $\geq$ 0.0, 20.5 $<$ 20.5), 0.0, 0.0]

The next equation in the logic table compares 20.5 to Complexity 2 = 20.5 and Complexity 3 = 21.85. For this equation, the first condition is true and the second condition is true. Thus, 20.5 is entered in the logic table.

IF [(20.5 $\geq$ 20.5, 20.5 $<$ 21.85), 20.5, 0.0]

For all the other equations in the table, the conditions are false and a 0.0 is entered. Memberships are selected when the complexity is selected and are entered in the table

when the conditions are both true.

The second set of logic equations in the complexity logic table select the complexity above the input complexity. The EXCEL formula is:

IF [(INPUT <= Complexity 1, INPUT < Complexity 2), Complexity 1=0.0]

Thus, when the input complexity of 20.5 is compared to Complexity 1 = 0.0 and Complexity 2 = 20.5, the first condition is false and the second condition is false. Thus, a zero is entered in the logic table.

IF [(20.5 <= 0.0, 20.5 < 20.5), 0.0, 0.0]

The next equation in the logic table compares 20.5 to Complexity 2 = 20.5 and Complexity 3 = 21.85. For this equation, the first condition is true and the second condition is true. However, this time 20.85 is entered into the logic table because it is the higher complexity. Again, the memberships associated with the complexity of 20.85 are entered in the logic table.

IF [(20.5 <= 20.5, 20.5 < 21.85), 21.85, 0.0]

Once the complexities and the associated memberships are selected, a linear regression calculation is used to determine the membership of the input complexity in each set. First the average complexity and the average membership for each fuzzy set is calculated.

The average complexity is $[(20.5 + 21.85) / 2] = 21.17$. The average membership in the low complexity fuzzy set is $[(0.899 + 0.837) / 2] = 0.868$. The average membership in the medium complexity fuzzy set is $[(0.101 + 0.156) / 2] = 0.129$. The average membership in the large fuzzy set is $[(0.000 + 0.007) / 2] = 0.003$.

The next step is to calculate the estimated regression equation for each membership set.

The form of the estimated regression equation is:

$$y = b_0 + (b_1 * x_{avg}).$$

$$b_1 = \sum ((x_i - x_{avg}) * (y_i - y_{avg})) / \sum (x_i - x_{avg})^2$$

$$b_0 = y_{avg} - (b_1 * x_{avg}).$$

For the small fuzzy set:

$$x_1 = 20.5$$

$$x_2 = 21.85$$

$$y_1 = 0.90$$

$$y_2 = 0.84$$

$$x_{avg} = 21.17$$

$$y_{avg} = 0.868$$

$$b_1 = \frac{((20.5 - 21.17) + (21.85 - 21.17)) * ((0.90 - 0.87) + (0.84 - 0.87))}{(20.5 - 21.17)^2 + (21.85 - 21.17)^2}$$

$$b_1 = -0.046$$

$$b_o = 0.868 - ((-0.046) * (20.5))$$

$$b_o = 1.837$$

$$y = 1.837 - (0.046 * \text{INPUT})$$

$$y = 1.837 - (0.046 * 20.5)$$

$$y = 0.899 \text{ (membership of 20.5 in the small fuzzy set)}$$

For the medium fuzzy set:

$$x_1 = 20.5$$

$$x_2 = 21.85$$

$$y_1 = 0.101$$

$$y_2 = 0.156$$

$$x_{\text{avg}} = 21.17$$

$$y_{\text{avg}} = 0.129$$

$$b_1 = 0.041$$

$$b_o = -0.736$$

$$y = -0.736 + (0.041 * \text{INPUT})$$

$$y = -0.736 + (0.041 * 20.5)$$

$$y = 0.101 \text{ (membership of 20.5 in the medium fuzzy set)}$$

For the large fuzzy set:

$$x_1 = 20.5$$

$$x_2 = 21.85$$

$$y_1 = 0.000$$

$$y_2 = 0.007$$

$$x_{avg} = 21.17$$

$$y_{avg} = 0.003$$

$$b_1 = 0.005$$

$$b_o = -0.101$$

$$y = -0.101 + (0.005 * \text{INPUT})$$

$$y = -0.101 + (0.005 * 20.5)$$

$$y = 0.000 \text{ (membership of 20.5 in the large fuzzy set)}$$

Once the memberships are calculated for the volume and complexity fuzzy sets, the rules determine the “cutoff” memberships. In the fuzzy rule table, the first, second and third rule compare the small volume to each of the complexity fuzzy set memberships calculated above: low, medium and high. The first three rules are:

Rule 1: $\text{Min } [0.929, 0.90] = 0.90$ Low cost fuzzy set

Rule 2: $\text{Min } [0.929, 0.10] = 0.10$ Low cost fuzzy set

Rule 3: $\text{Min } [0.929, 0.00] = 0.00$ Medium cost fuzzy set

The fourth, fifth and sixth rule compare the medium volume to each of the complexity fuzzy sets: low, medium and high calculated above. The next three rules are:

Rule 4: $\text{Min } [0.071, 0.090] = 0.071$ Low cost fuzzy set

Rule 5: $\text{Min } [0.071, 0.101] = 0.071$ Medium cost fuzzy set

Rule 6: $\text{Min } [0.071, 0.000] = 0.000$ Large cost fuzzy set

The seventh, eighth and ninth rule compare the large volume to each of the complexity fuzzy sets: low, medium and high calculated above. The next three rules are:

Rule 7: $\text{Min } [0.00, 0.90] = 0.00$ Medium cost fuzzy set

Rule 8: $\text{Min } [0.00, 0.101] = 0.00$ Large cost fuzzy set

Rule 9: $\text{Min } [0.00, 0.00] = 0.00$ Large cost fuzzy set

The “cutoff” memberships obtained from the rules are then used to obtain the “cutoff” memberships for each cost set. For the low cost set, the memberships from Rules 1, 2 and 4 are used to find the “cutoff” membership.

Low Cost “Cutoff” Membership: $\text{Max } [0.90, 0.10, 0.071] = 0.90$

For the medium cost set, the memberships from Rules 3, 5, and 7 are used to find the “cutoff” membership.

Medium Cost “Cutoff” Membership: $\text{Max } [0.00, 0.071, 0.00] = 0.071$

For the large cost set, the memberships from Rules 6, 8 and 9 are used to find the “cutoff” membership.

Large Cost “Cutoff” Membership: $\text{Max } [0.00, 0.00, 0.00] = 0.00$

Once the “cutoff” memberships are known for each cost fuzzy set, the logic equations in the cost logic table are used to determine the cost for each “cutoff” membership. The first two columns in the cost logic table are used to find the cost lower than the cutoff cost of the low cost fuzzy set. The second two columns in the cost logic table are used to find the cost higher than the cutoff cost of the low cost fuzzy set. For the low cost fuzzy set, a membership of 0.899 is used. The logic equation is the same as the logic equations used in the volume and complexity logic tables. However, this time the “cutoff” membership calculated by the rules is the input. Thus, the first equation compares 0.899 to the first low cost membership in the cost table and the second low cost membership in the cost table. The first condition is true and the second condition is true. Thus, the first input in Column 1 and 2 is 0.0 for the cost and 1.0 for the membership.

IF $[(0.899 < 1.0, 0.899 \geq 0.888), 1.0, 0.0]$

The second equation compares 0.899 to the second low cost membership and the third low cost membership in the cost table. For this equation, the first condition is false and the second condition is true. Thus, the second input in the table is \$0.0 for the cost and 0.0 for the membership, Column 1 and 2, respectively.

IF $[(0.899 < 0.888, 0.899 \geq 0.308), 0.888, 0.0]$

All other inputs in the first two column of the logic table are 0.0.

In the second two columns of the first section, the first equation compares 0.899 to the first low cost membership and the second low cost membership in the cost table. For this equation, the first condition is true and the second condition is true. The membership is 0.888 and the cost is \$0.126.

In the second section of the cost logic table, the cutoff costs are found for the medium cost fuzzy set. Since the medium cost fuzzy set is trapezoidal in shape, two costs must be determined for the cutoff membership. Thus, there are four sets of equations used to determine the cutoff costs. Columns 5 and 6 find the cost lower than the cutoff cost on the high cost side of the trapezoid. Columns 7 and 8 find the cost higher than the cutoff cost on the high cost side of the trapezoid. Columns 9 and 10 find the cost lower than the cutoff cost on the low cost side of the trapezoid. Columns 11 and 12 find the cost higher than the cutoff cost on the low cost side of the trapezoid. For the medium cost fuzzy set, a membership of 0.07 is used. For Columns 5, 6, 7 and 8, the logic equation is the same as the logic equations used in Columns 1, 2, 3 and 4. However, the conditions are reversed in Columns 9, 10, 11 and 12. These equations find the cost on the low cost side of the trapezoid. The new equation is:

IF $[(\text{cutoff} \geq \text{Membership 1}, \text{cutoff} < \text{Membership 2}), \text{Membership 1}, 0.0]$

In the third section of the cost logic table, the cutoff costs are found for the high cost fuzzy set. For the high cost fuzzy set, only one cutoff cost is required. Thus, there are two set of equations used to determine the cutoff cost. Columns 13, 14, 15 and 16 find the membership and the cost for the high cost fuzzy set. For the high cost fuzzy set, the same equation with the reversed conditions is used.

Once the costs above and below the cutoff memberships are determined, the spreadsheet calculates the cost at the cutoff membership. For the low cost fuzzy set in the extrusion example, the cost below the “cutoff” cost is \$0.0 and the cost above the “cutoff” cost is \$0.126. To find the cutoff cost a linear interpolation is made between the memberships and the costs.

The formula used to calculate the cost is:

$$C_{\text{cutoff}} = C_A - [(C_A - C_B) / (M_A - M_B) * (M_A - M_{\text{cutoff}})]$$

Where

C_A is the cost above the “cutoff” membership

C_B is the cost below the “cutoff” membership

M_A is the membership above the “cutoff” membership

M_B is the membership below the “cutoff” membership

M_{cutoff} is the “cutoff” membership

$$C_{\text{cutoff}} = \$0.0 - ((\$0.0 - \$0.126) * (1.0 - 0.899) / (1.0 - 0.888))$$

$$C_{\text{cutoff}} = \$0.114$$

For the medium cost fuzzy set in the extrusion example, the cost below the “cutoff” cost is \$0.00 and the cost above the “cutoff” cost is \$1.121 on the high cost side of the trapezoid. To find the cutoff cost, a linear interpolation is made between the memberships and the costs.

$$C_{\text{cutoff}} = C_A - [(C_A - C_B) / (M_A - M_B) * (M_A - M_{\text{cutoff}})]$$

$$C_{\text{cutoff}} = \$1.121 - ((\$1.121 - \$0.00) * (0.112 - 0.071) / (0.112 - 0.00))$$

$$C_{\text{cutoff}} = \$0.715$$

The cost below the “cutoff” cost is \$0.00 and the cost above the “cutoff” cost is \$0.126 on the low cost side of the trapezoid. To find the cutoff cost, a linear interpolation is made between the memberships and the costs.

$$C_{\text{cutoff}} = C_A - [(C_A - C_B) / (M_A - M_B) * (M_A - M_{\text{cutoff}})]$$

$$C_{\text{cutoff}} = \$0.00 - ((\$0.00 - \$0.126) * (0.112 - 0.071) / (0.112 - 0.000))$$

$$C_{\text{cutoff}} = \$0.080$$

For the high cost fuzzy set in the extrusion example, the cost below the “cutoff” cost is \$0.0 and the cost above the “cutoff” cost is \$0.126. To find the cutoff cost a linear interpolation is made between the memberships and the costs.

$$C_{\text{cutoff}} = C_A - [(C_A - C_B) / (M_A - M_B) * (M_A - M_{\text{cutoff}})]$$

$$C_{\text{cutoff}} = \$0.0 - ((\$0.0 - \$0.126) * (0.00035 - 0.00) / (0.00035 - 0.0))$$

$$C_{\text{cutoff}} = \$0.007$$

The estimated cost for the extrusion example is calculated using the cutoff cost (CC), the cutoff membership (CM) and the maximum cost (MC). First, the areas are calculated using the cutoff costs calculated above.

The area of the low cost fuzzy set is:

$$\text{Low Cost Area} = (CM * CC) + (0.5 * CM * (MC - CC))$$

$$\text{Low Cost Area} = (0.899 * \$0.114) + (0.5 * 0.899 * (\$1.121 - \$0.114))$$

$$\text{Low Cost Area} = \$0.5549$$

The area of the medium cost fuzzy set is:

$$\text{Medium Cost Area} = CM * ((MC + (\text{High Side Cutoff Cost} - \text{Low Side Cutoff Cost})) * 0.5)$$

$$\text{Medium Cost Area} = (0.071 * (\$1.121 + (\$0.715 - \$0.08))) * 0.5$$

$$\text{Medium Cost Area} = \$0.0625$$

The area of the high cost fuzzy set is:

$$\text{High Cost Area} = (CM * MC) + (0.5 * CM * CC)$$

$$\text{High Cost Area} = (0.00 * \$1.121) + (0.5 * 0.00 * \$0.126)$$

High Cost Area = \$0.00

The contributions for each of the cost sets are a function of the area, the cutoff cost [CC] and the maximum cost [MC].

The low cost contribution (LCC) for the low cost fuzzy set is:

$$LCC = \frac{[CC^2 * 0.5] + [[CC + [(MC-CC)*1/3]*0.5*(MC-CC)] * [Low Cost Area]}{[CC + (MC-CC)*0.5]}$$

$$LCC = \frac{[\$0.114^2 * 0.5 + [\$0.114 + [\$1.121-\$0.114]*1/3]*0.5*[\$1.121-\$0.114]]*0.555}{[\$0.114 + [\$1.121-\$0.114]*0.5]}$$

Low Cost Contribution = \$0.209

The contribution for the medium cost fuzzy set is:

Medium Cost Contribution = [High Cutoff Cost + Low Cutoff Cost] / 2 * [Medium Cost Area]

$$\text{Medium Cost Contribution} = [\$0.715 + \$0.080] / 2 * \$0.0625$$

Medium Cost Contribution = \$0.025

The high cost contribution for the high cost fuzzy set is a function of the maximum cost (MC), the high cutoff cost (HCC) and the low medium cutoff cost (LMCC).

$$\frac{[(MC-HCC)*[MC+HCC]/2] + [(LMCC + [(HCC-LMCC)*2/3]/2*[HCC-MCC])*LCA]}{[(MC-HCC) + [HCC-LMCC]*0.5]}$$

$$\frac{[(1.12-0.007)*[1.12+.007]/2] + [(0.08 + [(0.007-0.08)*2/3]/2*[0.007-0.08]) * 0.555]}{[(1.12-0.007) + [0.007-0.08]*0.5]}$$

High Cost Contribution = \$\$0.000

The estimated cost is the sum of the contribution divided by the sum of the areas.

Estimated Cost = (\$\$0.209 + \$\$0.025 + \$\$0.000) / (\$0.555 + \$0.062 + \$0.000)

Estimated Cost = \$0.379

Table 4-1 Stamped Component Model

		Volume	Low	Medium	Large
Volume =	0.883	0.000	1.000	0.000	0.000
		0.121	0.875	0.125	0.000
Complex =	132	0.136	0.765	0.220	0.015
		0.189	0.515	0.415	0.069
		0.316	0.258	0.542	0.200
		0.349	0.222	0.544	0.234
		0.375	0.198	0.541	0.261
		0.398	0.179	0.536	0.285
		0.596	0.078	0.434	0.488
		0.784	0.029	0.289	0.682
		0.883	0.012	0.204	0.784
		0.972	0.000	0.125	0.875

Logic Equations for Volume	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000
	0.784	0.029	0.289	0.682
	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000
	0.883	0.012	0.204	0.784
	0.000	0.000	0.000	0.000
	0.784	0.029	0.289	0.682
	0.883	0.012	0.204	0.784
	0.834	0.021	0.246	0.733
		-0.001	-0.004	0.005
	b1 =	-0.175	-0.854	1.029
bo =	0.166	0.959	-0.125	
	0.012	0.204	0.784	

Table 4-1 Stamped Component Model

Complexity	Low	Medium	High	E-coat Heat						
0.00	1.000	0.000	0.000	Shape	Primary	Plate	Treat	Deburr	Tumble	Mold
20.6	0.949	0.051	0.000	10.51	1.00	1.37	1.09	1.18	1.11	1.00
22.9	0.847	0.147	0.006	7.63	1.00	3.00	1.00	1.00	1.00	1.00
31.2	0.609	0.365	0.027	10.39	1.00	3.00	1.00	1.00	1.00	1.00
31.3	0.605	0.368	0.027	13.45	2.33	1.00	1.00	1.00	1.00	1.00
39.2	0.474	0.479	0.047	14.49	2.33	1.16	1.00	1.00	1.00	1.00
61.3	0.284	0.613	0.102	14.14	2.33	1.86	1.00	1.00	1.00	1.00
132.0	0.105	0.616	0.279	48.84	2.33	1.16	1.00	1.00	1.00	1.00
142.5	0.093	0.602	0.305	52.73	2.33	1.16	1.00	1.00	1.00	1.00
201.7	0.051	0.496	0.453	74.64	2.33	1.16	1.00	1.00	1.00	1.00
363.8	0.006	0.136	0.858	10.63	1.00	3.00	1.09	1.18	1.11	7.99
400.2	0.000	0.051	0.949							

Logic Equations for Complexity

	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000
	61.280	0.284	0.613	0.102
	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000
	61.280	0.284	0.613	0.102
	132.005	0.105	0.616	0.279
	96.642	0.195	0.615	0.191
	b1 =	-6.356	0.106	6.250
	bo =	-0.003	0.000	0.002
		0.440	0.611	-0.051
		0.105	0.616	0.279

Table 4-1 Stamped Component Model

Cost	Low	Medium	High	Material Cost	Process Cost
0.000	1.000	0.000	0.000		
0.040	0.841	0.159	0.000	0.0293	0.0112
0.047	0.698	0.276	0.026	0.0407	0.0066
0.070	0.421	0.465	0.115	0.0310	0.0388
0.079	0.352	0.496	0.152	0.0680	0.0112
0.089	0.294	0.515	0.191	0.0807	0.0087
0.102	0.239	0.521	0.240	0.0856	0.0162
0.117	0.186	0.513	0.300	0.1071	0.0101
0.170	0.079	0.413	0.509	0.1602	0.0101
0.211	0.033	0.300	0.667	0.2006	0.0101
0.232	0.015	0.233	0.751	0.2220	0.0101
0.255	0.000	0.159	0.841		

Fuzzy Rules

Rule 1	0.012	Low	0.105
Rule 2	0.012	Med	0.204
Rule 3	0.012	High	0.616
Rule 4	0.105		
Rule 5	0.204		
Rule 6	0.204		
Rule 7	0.105		
Rule 8	0.616		
Rule 9	0.279		

Cost Logic Table

Col 1	Col 2	Col 3	Col 4	Col 5	Col 6	Col 7	Col 8	Col 9	Col 10	Col 11	Col 12	Col 13	Col 14	Col 15	Col 16
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.040	0.159	0.047	0.276	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.117	0.186	0.170	0.079	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.170	0.509	0.211	0.667
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.232	0.233	0.255	0.159	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.117	0.186	0.170	0.079	0.232	0.233	0.255	0.159	0.040	0.159	0.047	0.276	0.170	0.509	0.211	0.667

Low Cutoff	High Med Cutoff	Low Med Cutoff	High Cutoff
0.157	0.241	0.043	0.198

Cost Calculation
(Center of Gravity Method)

Low Cost Contrib	0.0020
Med Cost Contrib	0.0066
High Cost Contrib	0.0150
Low Cost Area	0.0204
Medium Cost Area	0.0463
High Cost Area	0.0830
Estimated Cost =	0.157

Table 4-2 Small Injection Molded Component Model

		Volume	Low	Medium	Large
Volume = 0.844 Complex = 61.54		0.000	1.000	0.000	0.000
		0.144	0.845	0.155	0.000
		0.175	0.668	0.299	0.033
		0.207	0.541	0.391	0.068
		0.219	0.503	0.417	0.081
		0.354	0.252	0.522	0.226
		0.397	0.208	0.520	0.273
		0.409	0.197	0.517	0.286
		0.599	0.085	0.424	0.490
		0.787	0.028	0.279	0.693
		0.844	0.016	0.230	0.754
		0.928	0.000	0.155	0.845
Logic Equations for Volume		0.000	0.000	0.000	0.000
		0.000	0.000	0.000	0.000
		0.000	0.000	0.000	0.000
		0.000	0.000	0.000	0.000
		0.000	0.000	0.000	0.000
		0.000	0.000	0.000	0.000
		0.000	0.000	0.000	0.000
		0.000	0.000	0.000	0.000
		0.000	0.000	0.000	0.000
		0.000	0.000	0.000	0.000
		0.000	0.000	0.000	0.000
		0.000	0.000	0.000	0.000
		0.844	0.016	0.230	0.754
		0.000	0.000	0.000	0.000
		0.000	0.000	0.000	0.000
		0.000	0.000	0.000	0.000
		0.000	0.000	0.000	0.000
		0.000	0.000	0.000	0.000
		0.000	0.000	0.000	0.000
		0.000	0.000	0.000	0.000
		0.000	0.000	0.000	0.000
		0.000	0.000	0.000	0.000
		0.000	0.000	0.000	0.000
		0.000	0.000	0.000	0.000
		0.000	0.000	0.000	0.000
		0.000	0.000	0.000	0.000
		0.928	0.000	0.155	0.845
		0.844	0.016	0.230	0.754
		0.928	0.000	0.155	0.845
		0.886	0.008	0.193	0.800
			-0.001	-0.003	0.004
	b1 =	-0.184	-0.893	1.077	
	bo =	0.171	0.984	-0.155	
		0.02	0.23	0.75	

Table 4-2 Small Injection Molded Component Model

Complexity	Low	Medium	High	Shape Complexity	Primary Complexity
0.00	1.000	0.000	0.000	19.31	1.00
19.31	0.715	0.285	0.000	22.97	1.00
22.98	0.555	0.390	0.054	23.55	1.00
23.57	0.534	0.402	0.063	24.49	1.00
24.51	0.503	0.420	0.077	26.63	1.00
26.69	0.439	0.452	0.109	27.81	1.00
27.89	0.407	0.466	0.127	32.09	1.00
32.18	0.315	0.495	0.190	50.68	1.00
50.93	0.094	0.438	0.467	53.88	1.01
54.26	0.071	0.413	0.517	61.07	1.01
61.54	0.029	0.347	0.624		
67.69	0.000	0.285	0.715		

**Logic
Equations**

0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000
61.538	0.029	0.347	0.624
0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000
67.692	0.000	0.285	0.715
0.000	0.000	0.000	0.000
61.538	0.029	0.347	0.624
67.692	0.000	0.285	0.715
64.615	0.015	0.316	0.670
	-0.088	-0.192	0.280
b1 =	-0.005	-0.010	0.015
bo =	0.314	0.971	-0.285
	0.029	0.347	0.624

Table 4-2 Small Injection Molded Component Model

Cost	Low	Medium	High	Material	Process
				Cost	Cost
0.000	1.00	0.00	0.00		
0.024	0.717	0.283	0.000	0.0112	0.01307
0.027	0.627	0.345	0.028	0.0136	0.01308
0.029	0.549	0.394	0.057	0.0161	0.01308
0.030	0.523	0.409	0.068	0.0171	0.01308
0.041	0.314	0.495	0.191	0.0276	0.01310
0.044	0.269	0.501	0.230	0.0310	0.01311
0.045	0.257	0.502	0.241	0.0319	0.01311
0.060	0.123	0.463	0.413	0.0467	0.01314
0.075	0.043	0.373	0.584	0.0614	0.01316
0.079	0.025	0.339	0.636	0.0658	0.01317
0.086	0.000	0.283	0.717		

Fuzzy Rules

Rule 1	0.02	Low	0.029
Rule 2	0.02	Med	0.230
Rule 3	0.02	High	0.624
Rule 4	0.03		
Rule 5	0.23		
Rule 6	0.23		
Rule 7	0.03		
Rule 8	0.35		
Rule 9	0.62		

Cost Logic Table

Col 1	Col 2	Col 3	Col 4	Col 5	Col 6	Col 7	Col 8	Col 9	Col 10	Col 11	Col 12	Col 13	Col 14	Col 15	Col 16
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.024	0.283	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.075	0.043	0.079	0.025	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.075	0.584	0.079	0.636
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.086	0.283	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.075	0.043	0.079	0.025	0.086	0.283	0.000	0.000	0.000	0.000	0.024	0.283	0.075	0.584	0.079	0.636

Low Cutoff

0.078

High Med Cutoff

0.070

Low Med Cutoff

0.020

High Cutoff

0.078

Cost Calculation
(Center of Gravity Method)

Low Cost Contrib	0.0001
Med Cost Contrib	0.0007
High Cost Contrib	0.0015
Low Cost Area	0.0024
Medium Cost Area	0.0157
High Cost Area	0.0232
Estimated Cost =	\$9.055

Table 4-3 Large Injection Molded Component

Volume = 26.600
Complex = 92.26

Logic Equations for Volume

Table 4-3 Large Injection Molded Component Model

Complexity	Low	Medium	High	Shape Complexity	Primary Complexity
0.00	1.000	0.000	0.000	46.37	1.08
49.98	0.945	0.055	0.000	44.78	1.12
50.08	0.943	0.057	0.000	44.03	1.14
50.10	0.943	0.057	0.000	63.87	1.29
82.68	0.550	0.415	0.036	65.76	1.40
92.26	0.487	0.467	0.047	70.18	1.60
112.49	0.389	0.542	0.069	75.90	2.59
196.23	0.200	0.639	0.161	78.07	4.01
313.27	0.105	0.606	0.290	80.37	6.68
537.02	0.038	0.426	0.536	92.24	8.96
826.07	0.006	0.140	0.854		
908.67	0.000	0.055	0.945		

Logic Equations for Complexity

[illegible]

Table 4-3 Large Injection Molded Component Model

Cost	Low	Medium	High	Material Cost	Process Cost
0.000	1.000	0.000	0.000	0.530	0.014
0.544	0.920	0.080	0.000	0.772	0.015
0.787	0.612	0.353	0.035	0.881	0.015
0.896	0.528	0.421	0.051	1.645	0.017
1.662	0.247	0.589	0.163	2.074	0.018
2.092	0.180	0.594	0.226	2.713	0.021
2.734	0.119	0.561	0.320	4.415	0.034
4.449	0.042	0.386	0.571	5.403	0.053
5.456	0.020	0.261	0.719	6.118	0.088
6.206	0.008	0.164	0.829	6.391	0.118
6.509	0.004	0.123	0.873		
6.830	0.000	0.080	0.920		

Fuzzy Rules

Rule 1	0.18	Low	0.487
Rule 2	0.18	Med	0.467
Rule 3	0.05	High	0.220
Rule 4	0.49		
Rule 5	0.47		
Rule 6	0.05		
Rule 7	0.22		
Rule 8	0.22		
Rule 9	0.05		

Cost Logic Table

Col 1	Col 2	Col 3	Col 4	Col 5	Col 6	Col 7	Col 8
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.896	0.528	1.662	0.247	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	2.734	0.561	4.449	0.386
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.896	0.528	1.662	0.247	2.734	0.561	4.449	0.386

LowCutoff

1.007

HighMedCutoff

3.657

LowMedCutoff

1.103

HighCutoff

2049

Cost Calculation

(Center of Gravity Method)

LowCost Contrib	4.4249
Med Cost Contrib	5.2129
High Cost Contrib	4.8501
LowCost Area	1.9074
MediumCost Area	2.1899
High Cost Area	1.1559

Estimated Cost =	\$2.76
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Table 4.4 Rolled Component Model

Volume = Complexity =	13.016 116.9	Volume	Low	Medium	High
		0.000	1.000	0.000	0.000
		1.722	0.880	0.120	0.000
		1.886	0.793	0.195	0.012
		2.210	0.659	0.306	0.034
		2.963	0.461	0.452	0.087
		4.978	0.226	0.546	0.228
		5.371	0.201	0.544	0.255
		6.510	0.145	0.521	0.335
		7.232	0.118	0.497	0.385
		11.219	0.033	0.303	0.664
		13.016	0.012	0.199	0.789
		14.318	0.000	0.120	0.880
Logic Equations for Volume		0.000	0.000	0.000	0.000
		0.000	0.000	0.000	0.000
		0.000	0.000	0.000	0.000
		0.000	0.000	0.000	0.000
		0.000	0.000	0.000	0.000
		0.000	0.000	0.000	0.000
		0.000	0.000	0.000	0.000
		0.000	0.000	0.000	0.000
		0.000	0.000	0.000	0.000
		0.000	0.000	0.000	0.000
		0.000	0.000	0.000	0.000
		13.016	0.012	0.199	0.789
		0.000	0.000	0.000	0.000
		0.000	0.000	0.000	0.000
		0.000	0.000	0.000	0.000
		0.000	0.000	0.000	0.000
		0.000	0.000	0.000	0.000
		0.000	0.000	0.000	0.000
		0.000	0.000	0.000	0.000
		0.000	0.000	0.000	0.000
		0.000	0.000	0.000	0.000
		0.000	0.000	0.000	0.000
		0.000	0.000	0.000	0.000
		14.318	0.000	0.120	0.880
		13.016	0.012	0.199	0.789
		14.318	0.000	0.120	0.880
		13.667	0.006	0.159	0.835
			-0.008	-0.051	0.059
		b1 =	-0.009	-0.061	0.070
		bo =	0.133	0.987	-0.120
			0.01	0.20	0.79

Table 4.4 Rolled Component Model

Complexity	Low	Mdum	High	Shape Complex	Binary Complex			Material Complex
						Length	Material	
000	1.00	0.00	0.00	1594	1.00	1025	alum	1.00
1596	0900	0.10	0.00	1325	2.05	1050	steel	0.67
1817	0778	0.207	0.04	1364	2.30	11.75	steel	0.67
2098	0663	0.306	0.081	1461	1.90	1950	alum	1.00
2788	0473	0.482	0.075	1457	3.61	1850	steel	0.67
3520	0353	0.525	0.121	1517	2.56	2625	alum	1.00
3890	0310	0.545	0.144	2395	4.38	4488	alum	1.00
10499	0082	0.388	0.560	2442	4.79	4900	alum	1.00
11689	0087	0.329	0.634	2822	7.40	3788	steel	0.67
13960	0014	0.219	0.777	2753	7.86	4025	steel	0.67
14471	0010	0.181	0.809					
15918	0000	0.100	0.900					

Logic Equations
for
Complexity

0000	0000	0000	0000
0000	0000	0000	0000
0000	0000	0000	0000
0000	0000	0000	0000
0000	0000	0000	0000
0000	0000	0000	0000
0000	0000	0000	0000
0000	0000	0000	0000
0000	0000	0000	0000
116890	0087	0.329	0.634
0000	0000	0000	0000
0000	0000	0000	0000
0000	0000	0000	0000
0000	0000	0000	0000
0000	0000	0000	0000
0000	0000	0000	0000
0000	0000	0000	0000
0000	0000	0000	0000
139600	0014	0.219	0.777
0000	0000	0000	0000
0000	0000	0000	0000
0000	0000	0000	0000
116890	0087	0.329	0.634
139600	0014	0.219	0.777
128245	0025	0.249	0.706
	-0.252	-1.368	1.620
bl=	-0.001	-0.005	0.006
bo=	0.151	0.949	-0.100
	0.04	0.33	0.63

Table 4.4 Rolled Component Model

Cost	Low	Medium	High	Material Cost	Primary Cost		
0.000	1.000	0.000	0.000	0.192	0.004	10.25	alum
0.196	0.892	0.108	0.000	0.406	0.008	10.50	steel
0.414	0.365	0.516	0.119	0.475	0.009	11.75	steel
0.484	0.296	0.546	0.158	0.555	0.007	19.50	alum
0.562	0.240	0.559	0.201	0.598	0.010	26.25	alum
0.608	0.214	0.560	0.226	0.637	0.014	18.50	steel
0.651	0.193	0.558	0.250	1.250	0.017	44.88	alum
1.267	0.046	0.366	0.588	1.400	0.029	37.88	steel
1.429	0.029	0.294	0.677	1.450	0.019	49.00	alum
1.469	0.025	0.276	0.699	1.555	0.031	40.25	steel
1.586	0.015	0.222	0.763				
1.821	0.000	0.108	0.892				

Fuzzy Rules

Rule 1	0.01	Low	0.037
Rule 2	0.01	Med	0.199
Rule 3	0.01	High	0.634
Rule 4	0.04		
Rule 5	0.20		
Rule 6	0.20		
Rule 7	0.04		
Rule 8	0.33		
Rule 9	0.63		

Cost Logic Table

Col 1	Col 2	Col 3	Col 4	Col 5	Col 6	Col 7	Col 8	Col 9	Col 10
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.196	0.108
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1.267	0.046	1.429	0.029	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	1.586	0.222	1.821	0.108	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1.267	0.046	1.429	0.029	1.586	0.222	1.821	0.108	0.196	0.108

Low Cutoff
1.359

High Med Cutoff
1.634

Low Med Cutoff
0.244

High Cutoff
1.352

Cost Calculation
(Center of Gravity Method)

Low Cost Contrib	0.0465
Med Cost Contrib	0.2994
High Cost Contrib	0.8174
Low Cost Area	0.0581
Medium Cost Area	0.3188
High Cost Area	0.6490
Estimated Cost =	\$1.13

Table 4.5 Extrusion Component Model

Volume = 0.556 Complex = 20.5	Volume	Low	Medium	High
	0.000	1.000	0.000	0.000
	0.556	0.929	0.071	0.000
	1.355	0.339	0.559	0.102
	1.887	0.223	0.606	0.170
	2.989	0.115	0.574	0.311
	3.778	0.076	0.512	0.412
	3.961	0.069	0.495	0.436
	4.406	0.055	0.452	0.493
	5.176	0.036	0.372	0.591
	6.108	0.020	0.269	0.711
7.102	0.007	0.155	0.838	
7.812	0.000	0.071	0.929	
Logic Equations for Volume	0.000	0.000	0.000	0.000
	0.556	0.929	0.071	0.000
	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000
	0.556	0.929	0.071	0.000
	1.355	0.339	0.559	0.102
	0.956	0.6340	0.3149	0.0511
		-0.2356	0.1947	0.0409
	b1 =	-0.7380	0.6100	0.1280
	bo =	1.3392	-0.2680	-0.0712
		0.93	0.07	0.00

Table 4.5 Extrusion Component Model

Complexity	Low	Medium	High	Shape Complexity	Binary Complexity			Material Complexity
000	1000	0000	0000					
2050	0899	0101	0000	1874	164	steel	838	07
2185	0857	0156	0007	2188	100	alum	1388	10
2427	0744	0238	0019	1906	190	steel	1125	07
3207	0558	0415	0057	2441	131	alum	1825	10
4656	0339	0552	0128	2067	337	steel	1725	07
4896	0318	0542	0140	2567	191	alum	2650	10
6696	0215	0566	0229	2677	250	alum	3475	10
7573	0170	0558	0222	2778	273	alum	3788	10
16398	0024	0270	0706	2971	825	steel	4225	07
18475	0010	0182	0888	3010	918	steel	4700	07
20322	0000	0101	0899					

Logic Equations for Complexity

[illegible]

Table 4.5 Extrusion Component Model

Cost	Low	Medium	High	Material Cost	Primary Cost	
0.000	1.000	0.000	0.000	0.120	0.006	8.38
0.126	0.888	0.112	0.000	0.291	0.009	11.25
0.300	0.308	0.537	0.156	0.333	0.004	13.88
0.337	0.262	0.550	0.189	0.406	0.013	17.25
0.419	0.189	0.550	0.262	0.421	0.005	18.25
0.426	0.184	0.548	0.268	0.577	0.007	26.50
0.584	0.104	0.487	0.409	0.681	0.010	34.75
0.690	0.070	0.426	0.504	0.791	0.011	37.88
0.802	0.045	0.352	0.603	0.852	0.032	42.25
0.884	0.030	0.293	0.677	0.948	0.036	47.00
0.983	0.016	0.219	0.765			
1.121	0.000	0.112	0.888			

Fuzzy Rules

Rule 1	0.90	Low	0.90
Rule 2	0.10	Med	0.07
Rule 3	0.00	High	0.00
Rule 4	0.07		
Rule 5	0.07		
Rule 6	0.00		
Rule 7	0.00		
Rule 8	0.00		
Rule 9	0.00		

Cost Logic Table

Column1	Column2	Column3	Column4	Column5	Column6	Column7	Column8	Column9
0.000	1.000	0.126	0.888	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	1.121	0.112	0.000	0.000	0.000
0.000	1.000	0.126	0.888	1.121	0.112	0.000	0.000	0.000

LowCutoff
0.114

HighMedCutoff
0.715

LowMedCutoff
0.080

HighCutoff
0.007

Cost Calculation
(Center of Gravity Method)

LowCost Contrib	0.2093
Med Cost Contrib	0.0248
High Cost Contrib	0.0000
LowCost Area	0.5549
MediumCost Area	0.0625
High Cost Area	0.0000

Estimated Cost =	\$0.38
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5.0 Verification of the Fuzzy Logic Cost Estimation Model

To verify the models for the different fuzzy sets, the volumes and complexities for the sets were used as the input volumes and input complexities. Tables 5-1, 5-2, 5-3, 5-4 and 5-5 show the results. The tables show the component, the volume, the complexity, the actual cost, the estimated cost, the deviation from actual and the percent deviation of the estimated cost from the actual cost.

Table 5-1 shows the estimated costs for the stamped component set. The estimated costs for the stamped component set range from -0.1 % to -122.0 % of the actual cost. Five components have estimated costs higher than the actual and five have costs lower than the actual. The highest deviation from actual cost occurs for Component 2. The deviation is \$0.05. The smallest deviation from actual cost occurs for Component 1. The deviation is \$0.000.

Table 5-1 Stamped Component Set

Component	Volume	Complexity	Actual	Estimated	Deviation	% Deviation
			Cost	Cost		
1	0.121	363.8	\$0.07	\$0.07	\$0.000	-0.1%
2	0.136	22.9	\$0.04	\$0.09	-\$0.050	-122.2%
3	0.189	20.6	\$0.05	\$0.09	-\$0.045	-95.6%
4	0.316	31.2	\$0.08	\$0.12	-\$0.036	-45.8%
5	0.349	39.2	\$0.12	\$0.11	\$0.005	4.3%
6	0.375	31.3	\$0.09	\$0.12	-\$0.029	-32.4%
7	0.398	61.3	\$0.10	\$0.09	\$0.012	11.7%
8	0.596	142.5	\$0.17	\$0.14	\$0.029	17.2%
9	0.784	201.7	\$0.21	\$0.15	\$0.058	27.3%
10	0.883	132.0	\$0.23	\$0.16	\$0.074	32.0%

Table 5-2 shows the estimated cost for the small injection molded set. Six components have costs higher than the actual and four have costs lower than the actual. The estimated costs for the small injection molded set range from 0.0 % to 53.4 % of the actual cost. The highest deviation from actual cost occurs for Component 2. The deviation is \$0.014. The smallest deviation occurs for Components 7. The deviation is \$0.000.

Table 5-2 Small Injection Molded Set

Component	Volume	Complexity	Actual	Estimated	Deviation	% Deviation
			Cost	Cost		
1	0.144	19.31	\$0.024	\$0.030	-\$0.006	-23.5%
2	0.175	22.98	\$0.027	\$0.041	-\$0.014	-53.4%
3	0.207	23.57	\$0.029	\$0.041	-\$0.012	-40.3%
4	0.219	24.51	\$0.030	\$0.041	-\$0.011	-35.9%
5	0.354	26.69	\$0.041	\$0.044	-\$0.003	-8.1%
6	0.397	27.89	\$0.044	\$0.045	-\$0.001	-2.1%
7	0.409	32.18	\$0.045	\$0.045	\$0.000	0.0%
8	0.599	50.93	\$0.060	\$0.053	\$0.007	11.4%
9	0.787	54.26	\$0.075	\$0.057	\$0.018	23.5%
10	0.844	61.54	\$0.079	\$0.055	\$0.024	30.4%

Table 5-3 shows the estimated cost for the large injection molded component set. The estimated costs for the large injection molded component set ranges from -4.6 % to -324.4% of the actual cost. Six components have costs higher than the actual cost and four components have cost lower than the actual cost. The highest deviation from actual is \$2.16 for Component 9. The lowest deviation from the actual cost is \$0.13 for Component 6.

Table 5-3 Large Injected Molded Component Set

Component	Volume	Complexity	Actual	Estimated	Deviation	Deviation %
			Cost	Cost		
1	6.80	49.98	\$0.54	\$2.31	-\$1.77	-324.4%
2	9.90	50.08	\$0.79	\$2.45	-\$1.66	-210.9%
3	11.30	50.10	\$0.90	\$2.52	-\$1.62	-180.9%
4	21.10	82.68	\$1.66	\$2.70	-\$1.04	-62.6%
5	26.60	92.26	\$2.09	\$2.76	-\$0.67	-31.8%
6	34.79	112.49	\$2.73	\$2.86	-\$0.13	-4.6%
7	56.63	196.23	\$4.45	\$3.45	\$1.00	22.5%
8	69.30	313.27	\$5.46	\$3.83	\$1.63	29.9%
9	78.47	537.02	\$6.21	\$4.04	\$2.16	34.8%
10	81.97	826.07	\$6.51	\$4.43	\$2.08	32.0%
					0.00	

Table 5-4 shows the estimated cost for the rolled component set. The estimated costs for the rolled component set range from 10.8 % to 240.3 % over the actual cost for all components. Six components have costs higher than the actual cost and four components have cost lower than the actual cost. The largest deviation is \$0.52 for Component 8. The smallest deviation is -\$0.07 for Component 4.

Table 5-4 Rolled Component Set

Component	Volume	Complexity	Actual	Estimated	Deviation	% Deviation
			Cost	Cost		
1	1.722	16.0	\$0.20	\$0.67	-\$0.47	-240.3%
2	1.886	18.2	\$0.41	\$0.71	-\$0.30	-72.5%
3	2.210	20.9	\$0.48	\$0.73	-\$0.24	-50.0%
4	2.963	35.2	\$0.65	\$0.72	-\$0.07	-10.8%
5	4.978	27.8	\$0.56	\$0.77	-\$0.21	-36.7%
6	5.371	38.9	\$0.61	\$0.76	-\$0.15	-25.0%
7	6.510	139.6	\$1.43	\$1.05	\$0.38	26.7%
8	7.232	144.7	\$1.59	\$1.06	\$0.52	33.0%
9	11.219	105.0	\$1.27	\$1.06	\$0.20	16.1%
10	13.016	116.9	\$1.47	\$1.13	\$0.34	22.8%
					0.00	

Table 5-5 shows the estimated cost for the extruded component set. The estimated costs for the extruded component set range from 0.8 % to 30.5 % over the actual cost for all components. Six components have costs higher than the actual cost and four components have costs lower than the actual cost. The largest deviation is \$0.159 for Component 7. The smallest deviation is \$0.005 for Component 9.

Table 5-5 Extruded Component Set

Component	Volume	Complexity	Actual	Estimated	Deviation	Material	% Deviation
			Cost	Cost			
1	0.556	20.50	\$0.13	\$0.38	-\$0.25	steel	-200.8%
2	1.355	24.27	\$0.30	\$0.48	-\$0.18	steel	-60.7%
3	1.887	46.56	\$0.42	\$0.45	-\$0.03	steel	-7.4%
4	2.989	21.85	\$0.34	\$0.49	-\$0.15	alum	-45.4%
5	3.778	32.07	\$0.43	\$0.53	-\$0.10	alum	-24.4%
6	3.961	163.93	\$0.88	\$0.68	\$0.21	steel	23.5%
7	4.406	184.75	\$0.98	\$0.67	\$0.31	steel	31.8%
8	5.176	49.0	\$0.58	\$0.59	\$0.00	alum	-0.2%
9	6.108	67.0	\$0.69	\$0.63	\$0.06	alum	8.6%
10	7.102	75.7	\$0.80	\$0.66	\$0.14	alum	18.0%
					0.00		

The results show that the smaller sized components with low complexities are estimated high for all of the component sets. This means an additional fuzzy set is needed to model the smaller, less complex parts. Thus, three additional sets are defined for each component set; a very low volume set, a very low complexity set and a very low cost set. The memberships are divided between the very low volume set and the low volume set, the very low complexity set and the low complexity set, the very low cost set and the low cost set. The assumption is made that the low volumes, low complexities and low costs are only in the very low sets. Thus, all other volumes, complexities and costs have a

membership of 0.0 in the very low sets. In addition, the low volumes, low complexities and low costs have a 0.0 membership in the low fuzzy sets.

The addition of the very low fuzzy sets adds additional rules to the model. Instead of $3 \times 3 = 9$ rules there are now $4 \times 4 = 16$ rules. The new rules are shown in Table 5.6.

Table 5-6 Fuzzy Rules for New Models

	Very Low Volume	Low Volume	Medium Volume	Large Volume
Very Low Complexity	Very Low Cost	Very Low Cost	Very Low Cost	Medium Cost
Low Complexity	Very Low Cost	Low Cost	Low Cost	Medium Cost
Medium Complexity	Low Cost	Medium Cost	Medium Cost	High Cost
High Complexity	Low Cost	High Cost	High Cost	High Cost

For the stamped component set, the very low volume set contains the smallest volumes 0.121 in^3 , 0.136 in^3 , 0.189 in^3 and 0.316 in^3 . The very low complexity set contains the lowest complexities of 20.6, 22.9, 31.2 and 31.3. The very low cost set contains the lowest costs of \$0.0405 and \$0.0472. Table 5-7 shows the new model with the additional fuzzy sets.

Table 5-7 New Stamp Component Model

		Volume = 0.398 Complex = 61.3					
		Volume	Very Low	Low	Medium	Large	
Volume = 0.398 Complex = 61.3	0.000	1.000	0.000	0.000	0.000		
	0.121	0.875	0.000	0.125	0.000		
	0.136	0.765	0.000	0.220	0.015		
	0.189	0.515	0.000	0.415	0.069		
	0.316	0.258	0.000	0.542	0.200		
	0.349	0.000	0.222	0.544	0.234		
	0.375	0.000	0.198	0.541	0.261		
	0.398	0.000	0.179	0.536	0.285		
	0.596	0.000	0.078	0.434	0.488		
	0.784	0.000	0.029	0.289	0.682		
	0.883	0.000	0.012	0.204	0.784		
	0.972	0.000	0.000	0.125	0.875		

[illegible]

Table 5-7 New Stamp Component Model

Complexity	Very Low	Low	Medium	High	E-coat Heat						
					Shape	Primary	Plate	Treat	Deburr	Tumble	Mold
0.00	1.000	0.000	0.000	0.000	10.51	1.00	1.37	1.09	1.18	1.11	1.00
20.6	0.949	0.000	0.051	0.000	7.63	1.00	3.00	1.00	1.00	1.00	1.00
22.9	0.847	0.000	0.147	0.006	10.39	1.00	3.00	1.00	1.00	1.00	1.00
31.2	0.609	0.000	0.365	0.027	13.45	2.33	1.00	1.00	1.00	1.00	1.00
31.3	0.605	0.000	0.368	0.027	14.49	2.33	1.16	1.00	1.00	1.00	1.00
39.2	0.000	0.474	0.479	0.047	14.14	2.33	1.86	1.00	1.00	1.00	1.00
61.3	0.000	0.284	0.613	0.102	48.84	2.33	1.16	1.00	1.00	1.00	1.00
91.0	0.000	0.175	0.649	0.176	52.73	2.33	1.16	1.00	1.00	1.00	1.00
132.0	0.000	0.105	0.616	0.279	74.64	2.33	1.16	1.00	1.00	1.00	1.00
142.5	0.000	0.093	0.602	0.305	10.63	1.00	3.00	1.09	1.18	1.11	7.99
201.7	0.000	0.051	0.496	0.453							
363.8	0.000	0.006	0.136	0.858							
400.2	0.000	0.000	0.051	0.949							

Logic Equations for Complexity

	0.000	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000	0.000
61.280	0.000	0.284	0.613	0.102	
0.000	0.000	0.000	0.000	0.000	
0.000	0.000	0.000	0.000	0.000	
0.000	0.000	0.000	0.000	0.000	
0.000	0.000	0.000	0.000	0.000	
0.000	0.000	0.000	0.000	0.000	
0.000	0.000	0.000	0.000	0.000	
	0.000	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000	0.000
132.005	0.000	0.105	0.616	0.279	
0.000	0.000	0.000	0.000	0.000	
0.000	0.000	0.000	0.000	0.000	
0.000	0.000	0.000	0.000	0.000	
0.000	0.000	0.000	0.000	0.000	
0.000	0.000	0.000	0.000	0.000	
	61.280	0.000	0.284	0.613	0.102
	132.005	0.000	0.105	0.616	0.279
	96.642	0.000	0.195	0.615	0.191
		0.000	-6.356	0.106	6.250
b1 =	0.000	-0.003	0.000	0.000	0.002
bo =	0.000	0.440	0.611	-0.051	
	0.000	0.284	0.613	0.102	

Table 5-7 New Stamp Component Model

Cost	Very Low	Low	Medium	High		
0.0000	1.000	0.000	0.000	0.000	Material	Process
0.0405	0.872	0.000	0.159	0.000	Cost	Cost
0.0472	0.729	0.000	0.276	0.022	0.0293	0.0112
0.0698	0.000	0.452	0.465	0.094	0.0407	0.0066
0.0792	0.000	0.383	0.496	0.123	0.0310	0.0388
0.0894	0.000	0.325	0.515	0.156	0.0680	0.0112
0.1018	0.000	0.270	0.521	0.195	0.0807	0.0087
0.1172	0.000	0.217	0.513	0.244	0.0856	0.0162
0.1703	0.000	0.110	0.413	0.413	0.1071	0.0101
0.2107	0.000	0.064	0.300	0.541	0.1602	0.0101
0.2321	0.000	0.046	0.233	0.609	0.2006	0.0101
0.3150	0.000	0.000	0.159	0.872	0.2220	0.0101

Fuzzy Rules

Rule 1	0.765	Very Low	0.765
Rule 2	0.000	Low	0.147
Rule 3	0.147	Med	0.147
Rule 4	0.006	High	0.015
Rule 5	0.000		
Rule 6	0.000		
Rule 7	0.000		
Rule 8	0.000		
Rule 9	0.220		
Rule 10	0.000		
Rule 11	0.147		
Rule 12	0.006		
Rule 13	0.015		
Rule 14	0.000		
Rule 15	0.015		
Rule 16	0.006		

Cost Logic Table

Col 1	Col 2	Col 3	Col 4	Col 5	Col 6	Col 7	Col 8	Col 9
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.040	0.872	0.047	0.729	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.047
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.117	0.217	0.170	0.110	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.040	0.872	0.047	0.729	0.117	0.217	0.170	0.110	0.047

Low Cutoff

0.046

High Low Cutoff

0.152

Low Low Cutoff

0.055

High Med Cutoff

0.291

Low Med Cutoff

0.037

High Cutoff

0.045

Cost Calculation

(Center of Gravity Method)

Very Low Cost Area	0.003
Low Cost Contrib	0.003
Med Cost Contrib	0.007
High Cost Contrib	0.001
Very Low Cost Area	0.138
Low Cost Area	0.030
Medium Cost Area	0.042
High Cost Area	0.004
Estimated Cost =	0.065

For the new stamped model, the maximum cost is raised to \$0.315 (see Appendix A). The maximum volume and complexity remain at ten percent over the largest component volume and complexity. Table 5-8 shows the new cost estimates for the stamped component set.

Table 5-8 Cost Estimates from the New Stamped Component Model

Component	Volume	Complexity	Actual	Estimated	Deviation	% Deviation
			Cost	Cost		
1	0.121	363.8	0.070	0.075	-0.005	-7.6%
2	0.136	22.9	0.041	0.065	-0.025	-60.5%
3	0.189	20.6	0.047	0.056	-0.009	-18.6%
4	0.316	31.2	0.079	0.093	-0.014	-17.7%
5	0.349	39.2	0.117	0.102	0.015	12.9%
6	0.375	31.3	0.089	0.098	-0.009	-9.6%
7	0.398	61.3	0.102	0.099	0.003	2.9%
8	0.596	142.5	0.170	0.161	0.009	5.3%
9	0.784	201.7	0.211	0.176	0.034	16.3%
10	0.883	132.0	0.232	0.186	0.046	19.7%
0.00						

The estimated costs for the stamped component set range from 2.9 % to -60.5 % of the actual cost. Five components have estimated costs higher than the actual and five have costs lower than the actual. The highest deviation from actual cost still occurs for Component 2. However, the deviation is half of the previous deviation. The deviation is now \$0.025. The smallest deviation from actual cost now occurs for Component 7 instead of Component 1. The deviation is \$0.003. Overall the new stamped model generates estimated costs significantly lower than the original stamped model. In fact if Component 2 were removed from the stamped component set all of the estimated cost

would be within 20% of the actual cost. The estimated cost of Component 2 is higher because this component has a lower complexity and is also smaller than all the other components except Component 1. The cost of Component 1 is closer to actual because Component 1 has a high complexity. Components as small as Component 2 with low complexities need to be placed in a separate component set.

For the small injection molded component set, the very low volume set contains the smallest volumes 0.144 in³, 0.175 in³, 0.207 in³ and 0.219 in³. The very low complexity set contains the lowest complexities of 19.31, 22.98 and 23.7. The very low cost set contains the lowest costs of \$0.024, \$0.027 and \$0.029. Table 5-9 shows the new model with the additional fuzzy sets.

Table 5-9 New Small Injection Molded Set

Volume = 0.844 Complex = 61.54	Volume	Very Low	Low	Medium	Large
	0.000	1.000	0.000	0.000	0.000
	0.144	0.845	0.000	0.155	0.000
	0.175	0.668	0.000	0.299	0.033
	0.207	0.541	0.000	0.391	0.068
	0.219	0.503	0.000	0.417	0.081
	0.354	0.000	0.252	0.774	0.226
	0.397	0.000	0.208	0.727	0.273
	0.409	0.000	0.197	0.714	0.286
	0.599	0.000	0.085	0.510	0.490
	0.787	0.000	0.028	0.307	0.693
0.844	0.000	0.016	0.246	0.754	
0.928	0.000	0.000	0.155	0.845	
Logic Equations for Volume	0.000	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000	0.000
	0.844	0.000	0.016	0.246	0.754
	0.000	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000	0.000
	0.928	0.000	0.000	0.155	0.845
	0.844	0.000	0.016	0.246	0.754
	0.928	0.000	0.000	0.155	0.845
	0.886	0.000	0.008	0.200	0.800
		0.000	-0.001	-0.004	0.004
	b1 =	0.001	-0.184	-1.078	1.077
	bo =	-0.001	0.171	1.156	-0.155
		0.00	0.02	0.25	0.75

Table 5-9 New Small Injection Molded Set

Complexity	Very Low	Low	Medium	High	Shape Complexity	Primary Complexity
0.00	1.000	0.000	0.000	0.000	19.31	1.00
19.31	0.715	0.000	0.285	0.000	22.97	1.00
22.98	0.555	0.000	0.390	0.054	23.55	1.00
23.57	0.534	0.000	0.402	0.063	24.49	1.00
24.51	0.000	0.503	0.420	0.077	26.63	1.00
26.69	0.000	0.439	0.452	0.109	27.81	1.00
27.89	0.000	0.407	0.466	0.127	32.09	1.00
32.18	0.000	0.315	0.495	0.190	50.68	1.00
50.93	0.000	0.094	0.438	0.467	53.88	1.01
54.26	0.000	0.071	0.413	0.517	61.07	1.01
61.54	0.000	0.029	0.347	0.624		
67.69	0.000	0.000	0.285	0.715		

Logic
Equations

0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000
61.538	0.000	0.029	0.347	0.624
0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000
67.692	0.000	0.000	0.285	0.715
0.000	0.000	0.000	0.000	0.000
61.538	0.000	0.029	0.347	0.624
67.692	0.000	0.000	0.285	0.715
64.615	0.000	0.015	0.316	0.670
	0.000	-0.088	-0.192	0.280
b1 =	0.000	-0.005	-0.010	0.015
bo =	0.000	0.314	0.971	-0.285
	0.000	0.029	0.347	0.624

Table 5-9 New Small Injection Molded Set

Cost	Very Low	Low	Medium	High	Material	Process
					Cost	Cost
0.000	1.000	0.000	0.000	0.000		
0.024	0.748	0.000	0.253	-0.001	0.0112	0.01307
0.027	0.489	0.000	0.488	0.023	0.0136	0.01308
0.029	0.432	0.000	0.518	0.049	0.0161	0.01308
0.030	0.000	0.554	0.387	0.059	0.0171	0.01308
0.041	0.000	0.345	0.487	0.168	0.0276	0.01310
0.044	0.000	0.299	0.498	0.202	0.0310	0.01311
0.045	0.000	0.288	0.500	0.212	0.0319	0.01311
0.060	0.000	0.154	0.481	0.365	0.0467	0.01314
0.075	0.000	0.074	0.410	0.516	0.0614	0.01316
0.079	0.000	0.056	0.382	0.562	0.0658	0.01317
0.097	0.000	-0.001	0.253	0.748		

Fuzzy Rules

Rule 1	0.000	Very Low	0.000
Rule 2	0.000	Low	0.029
Rule 3	0.000	Med	0.246
Rule 4	0.000	High	0.624
Rule 5	0.000		
Rule 6	0.016		
Rule 7	0.016		
Rule 8	0.016		
Rule 9	0.000		
Rule 10	0.029		
Rule 11	0.246		
Rule 12	0.246		
Rule 13	0.000		
Rule 14	0.029		
Rule 15	0.347		
Rule 16	0.624		

Cost Logic Table

Col 1	Col 2	Col 3	Col 4	Col 5	Col 6	Col 7	Col 8	Col 9	Col 10	Col 11	Col 12	Col 13	Col 14	Col 15	Col 16
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.029	0.432	0.030	0.000	0.000	0.000	0.000	0.000	0.029	0.000	0.030	0.554	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	-0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.097	0.253	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.029	0.432	0.030	0.000	0.079	0.056	0.097	0.000	0.029	0.000	0.030	0.554	0.097	0.253	0.000	0.000

Low Cutoff	High Low Cutoff	Low Low Cutoff	High Med Cutoff	Low Med Cutoff	High Cutoff
0.030	0.088	0.029	0.094	0.024	0.085

Cost Calculation
(Center of Gravity Method)

Very Low Cost Area	0.0000
Low Cost Contrib	0.0001
Med Cost Contrib	0.0012
High Cost Contrib	0.0019
Very Low Cost Area	0.0000
Low Cost Area	0.0022
Medium Cost Area	0.0206
High Cost Area	0.0267
Estimated Cost =	0.0659

For the new small injection molded model, the maximum cost is raised to \$0.097 (see Appendix A). The maximum volume and complexity remain at ten percent over the largest component volume and complexity. Table 5-10 shows the new cost estimates for the stamped component set.

Table 5-10 New Cost Estimates for the Small Injection Molded Set

Component	Volume	Complexity	Actual	Estimated	Deviation	% Deviation
			Cost	Cost		
1	0.144	19.31	0.024	0.023	0.002	7.0%
2	0.175	22.98	0.027	0.034	-0.007	-26.5%
3	0.207	23.57	0.029	0.035	-0.005	-18.7%
4	0.219	24.51	0.030	0.035	-0.005	-15.4%
5	0.354	26.69	0.041	0.049	-0.008	-20.1%
6	0.397	27.89	0.044	0.050	-0.006	-14.2%
7	0.409	32.18	0.045	0.050	-0.005	-11.3%
8	0.599	50.93	0.060	0.060	0.000	-0.6%
9	0.787	54.26	0.075	0.063	0.012	15.9%
10	0.844	61.54	0.079	0.066	0.013	16.8%

The estimated costs for the small injection molded component set range from -0.6 % to -26.5 % of the actual cost. Six components have estimated costs higher than the actual and four have costs lower than the actual. The highest deviation from actual cost still occurs for Component 2. However, the deviation is half of the previous deviation. The deviation is now \$0.007. The smallest deviation from actual cost now occurs for Component 8 instead of Component 7. The deviation is \$0.000. Overall the new small injection molded model generates estimated costs significantly lower than the small injection molded model. The estimated costs are now within 26.5% of the actual cost.

For the large injection molded component set, the very low volume set contains the smallest volumes 6.8 in³, 9.9 in³, 11.3 in³ and 21.1 in³. The very low complexity set contains the lowest complexities of 49.98, 50.08, 50.1, 82.68 and 92.26. The very low cost set contains the lowest cost of \$0.544. Table 5-11 shows the new model with the additional fuzzy sets.

Table 5-11 New Large Injection Molded Set

		Volume	Very Low	Low	Medium	High
Volume = Complex =	81.970 826.07	0.000	1.000	0.000	0.000	0.000
		6.800	0.918	0.000	0.075	0.007
		9.900	0.605	0.000	0.351	0.045
		11.300	0.520	0.000	0.419	0.061
		21.100	0.240	0.000	0.580	0.180
		26.600	0.000	0.174	0.580	0.246
		34.790	0.000	0.113	0.541	0.345
		56.628	0.000	0.038	0.353	0.609
		69.300	0.000	0.016	0.222	0.762
		78.470	0.000	0.005	0.123	0.873
		81.970	0.000	0.001	0.084	0.915
		82.790	0.000	0.000	0.075	0.925
Logic Equations for Volume		0.00	0.00	0.00	0.00	0.00
		0.00	0.00	0.00	0.00	0.00
		0.00	0.00	0.00	0.00	0.00
		0.00	0.00	0.00	0.00	0.00
		0.00	0.00	0.00	0.00	0.00
		0.00	0.00	0.00	0.00	0.00
		0.00	0.00	0.00	0.00	0.00
		0.00	0.00	0.00	0.00	0.00
		0.00	0.00	0.00	0.00	0.00
		0.00	0.00	0.00	0.00	0.00
		0.00	0.00	0.00	0.00	0.00
		81.97	0.00	0.00	0.08	0.92
		0.00	0.00	0.00	0.00	0.00
		0.00	0.00	0.00	0.00	0.00
		0.00	0.00	0.00	0.00	0.00
		0.00	0.00	0.00	0.00	0.00
		0.00	0.00	0.00	0.00	0.00
		0.00	0.00	0.00	0.00	0.00
		0.00	0.00	0.00	0.00	0.00
		0.00	0.00	0.00	0.00	0.00
		0.00	0.00	0.00	0.00	0.00
		0.00	0.00	0.00	0.00	0.00
		0.00	0.00	0.00	0.00	0.00
		82.79	0.00	0.00	0.07	0.93
		81.97	0.00	0.00	0.08	0.92
		82.79	0.00	0.00	0.07	0.93
		82.38	0.00	0.00	0.08	0.92
			0.00	0.00	0.00	0.00
		b1 =	0.00	0.00	-0.01	0.01
		bo =	0.00	0.08	0.99	-0.08
			0.00	0.00	0.08	0.92

Table 5-11 New Large Injection Molded Set

Complexity	Very Low	Low	Medium	High	Shape Complexity	Primary Complexity
0.00	1.000	0.000	0.000	0.000	46.37	1.08
49.98	0.945	0.940	0.055	0.000	44.78	1.12
50.08	0.943	0.938	0.057	0.000	44.03	1.14
50.10	0.943	0.938	0.057	0.000	63.87	1.29
82.68	0.550	0.545	0.411	0.039	65.76	1.40
92.26	0.487	0.482	0.463	0.051	70.18	1.60
112.49	0.000	0.384	0.541	0.075	75.90	2.59
196.23	0.000	0.195	0.630	0.175	78.07	4.01
313.27	0.000	0.100	0.585	0.315	80.37	6.68
537.02	0.000	0.033	0.383	0.584	92.24	8.96
826.07	0.000	0.001	0.069	0.930		
834.33	0.000	0.000	0.060	0.940		

0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000
826.065	0.000	0.001	0.069	0.930
0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000
834.326	0.000	0.000	0.060	0.940
0.000	0.000	0.000	0.000	0.000
826.065	0.000	0.001	0.069	0.930
834.326	0.000	0.000	0.060	0.940
830.195	0.000	0.000	0.065	0.935
	0.000	-0.002	-0.038	0.041
b1 =	0.000	0.000	-0.001	0.001
bo =	0.000	0.051	1.000	-0.060
	0.00	0.00	0.07	0.93

Table 5-11 New Large Injection Molded Set

Cost	Very Low	Low	Medium	High	Material	Process
					Cost	Cost
0.000	1.000	0.000	0.000	0.000		
0.544	0.933	0.000	0.067	0.000	0.530	0.014
0.787	0.000	0.625	0.345	0.030	0.772	0.015
0.896	0.000	0.541	0.417	0.043	0.881	0.015
1.662	0.000	0.260	0.603	0.137	1.645	0.017
2.092	0.000	0.193	0.617	0.190	2.074	0.018
2.734	0.000	0.132	0.599	0.268	2.713	0.021
4.449	0.000	0.055	0.466	0.479	4.415	0.034
5.456	0.000	0.033	0.365	0.602	5.403	0.053
6.206	0.000	0.021	0.285	0.694	6.118	0.088
6.509	0.000	0.017	0.252	0.732	6.391	0.118
8.150	0.000	0.000	0.067	0.933		

Fuzzy Rules

Rule 1	0.000	Very Low	0.000
Rule 2	0.000	Low	0.001
Rule 3	0.000	Med	0.069
Rule 4	0.000	High	0.915
Rule 5	0.000		
Rule 6	0.001		
Rule 7	0.001		
Rule 8	0.001		
Rule 9	0.000		
Rule 10	0.001		
Rule 11	0.069		
Rule 12	0.084		
Rule 13	0.000		
Rule 14	0.001		
Rule 15	0.069		
Rule 16	0.915		

Cost Logic Table

[illegible]

Low Cutoff	High Low Cutoff	Low Low Cutoff	High Med Cutoff	Low Med Cutoff	High Cutoff
0.787	8.056	0.545	8.131	0.546	8.004

Cost Calculation
(Center of Gravity Method)

Very Low Cost Contrib	0.0000
Low Cost Contrib	0.0322
Med Cost Contrib	2.3684
High Cost Contrib	19.9082
Very Low Cost Area	0.0000
Low Cost Area	0.0075
Medium Cost Area	0.5459
High Cost Area	3.5459
Estimated Cost =	5.4421

For the new large injection molded model, the maximum cost is raised to \$8.15 (see Appendix A). The maximum volume and complexity remain at ten percent over the largest component volume and complexity. Table 5-12 shows the new cost estimates for the large injection molded component set.

Table 5-12 New Cost Estimates for the Large Injection Molded Set

Component	Volume	Complexity	Actual Cost	Estimated Cost	Deviation	Deviation %
1	6.80	49.98	\$0.54	\$0.84	-\$0.30	-54.9%
2	9.90	50.08	\$0.79	\$1.03	-\$0.24	-30.4%
3	11.30	50.10	\$0.90	\$1.13	-\$0.24	-26.7%
4	21.10	82.68	\$1.66	\$1.85	-\$0.19	-11.3%
5	26.60	92.26	\$2.09	\$2.06	\$0.03	1.3%
6	34.79	112.49	\$2.73	\$2.83	-\$0.09	-3.3%
7	56.63	196.23	\$4.45	\$3.93	\$0.52	11.6%
8	69.30	313.27	\$5.46	\$4.44	\$1.02	18.6%
9	78.47	537.02	\$6.21	\$4.91	\$1.29	20.9%
10	81.97	826.07	\$6.51	\$5.44	\$1.07	16.4%

The estimated costs for the stamped component set range from 1.3 % to -54.9 % of the actual cost. Five components have estimated costs higher than the actual and five have costs lower than the actual. The highest deviation from actual cost still occurs for Component 1. The deviation is \$0.30. The smallest deviation from actual cost now occurs for Component 5 instead of Component 6. The deviation is \$0.09. Overall the new large injection molded model generates estimated costs significantly lower than the original large injection molded model. The estimated costs for Components 3 through 10 are now within 26.7% of the actual cost. The estimated cost of Components 1 and 2 are higher because these components have a lower and are smaller than the other components

in the set. Components of this size need to be placed in a separate component set.

For the rolled component set, the very low volume set contains the smallest volumes 1.722 in³, 1.866 in³ and 2.21 in³. The very low complexity set contains the lowest complexities of 15.96, 18.17, 20.93, 27.83, 35.2 and 38.9. The very low cost set contains the lowest cost of \$0.196. Table 5-13 shows the new model with the additional fuzzy sets.

Table 5-13 New Rolled Component Model

		Volume	Very Low	Low	Medium	High
Volume = Complexity =	7.232 144.7	0.000	1.000	0.000	0.000	0.000
		1.722	0.880	0.000	0.120	0.000
		1.886	0.793	0.000	0.195	0.012
		2.210	0.659	0.000	0.306	0.034
		2.963	0.000	0.461	0.452	0.087
		4.978	0.000	0.226	0.546	0.228
		5.371	0.000	0.201	0.544	0.255
		6.510	0.000	0.145	0.521	0.335
		7.232	0.000	0.118	0.497	0.385
		11.219	0.000	0.033	0.303	0.664
		13.016	0.000	0.012	0.199	0.789
		14.318	0.000	0.000	0.120	0.880
Logic Equations for Volume		0.000	0.00	0.000	0.000	0.000
		0.000	0.00	0.000	0.000	0.000
		0.000	0.00	0.000	0.000	0.000
		0.000	0.00	0.000	0.000	0.000
		0.000	0.00	0.000	0.000	0.000
		0.000	0.00	0.000	0.000	0.000
		0.000	0.00	0.000	0.000	0.000
		0.000	0.00	0.000	0.000	0.000
		7.232	0.00	0.118	0.497	0.385
		0.000	0.00	0.000	0.000	0.000
		0.000	0.00	0.000	0.000	0.000
		0.000	0.00	0.000	0.000	0.000
		0.000	0.00	0.000	0.000	0.000
		0.000	0.00	0.000	0.000	0.000
		0.000	0.00	0.000	0.000	0.000
		0.000	0.00	0.000	0.000	0.000
		0.000	0.00	0.000	0.000	0.000
		0.000	0.00	0.000	0.000	0.000
		11.219	0.00	0.033	0.303	0.664
		0.000	0.00	0.000	0.000	0.000
		0.000	0.00	0.000	0.000	0.000
		7.232	0.00	0.118	0.497	0.385
		11.219	0.00	0.033	0.303	0.664
		9.226	0.00	0.076	0.400	0.524
			0.00	-0.169	-0.386	0.555
		b1 =	0.00	-0.021	-0.049	0.070
		bo =	0.00	0.272	0.848	-0.120
			0.00	0.12	0.50	0.39

Table 5-13 New Rolled Component Model

Complexity	Very Low	Low	Medium	High	Shape Complex	Primary Complex	Length	Material	Material Complex
0.00	1.000	0.00	0.000	0.000	15.94	1.00	10.25	alum	1.00
15.96	0.900	0.000	0.100	0.000	13.25	2.05	10.50	steel	0.67
18.17	0.778	0.000	0.207	0.014	13.64	2.30	11.75	steel	0.67
20.93	0.663	0.000	0.306	0.031	14.61	1.90	19.50	alum	1.00
27.83	0.473	0.000	0.452	0.075	14.57	3.61	18.50	steel	0.67
35.20	0.353	0.000	0.525	0.121	15.17	2.56	26.25	alum	1.00
38.90	0.310	0.000	0.545	0.144	23.95	4.38	44.88	alum	1.00
104.99	0.000	0.052	0.388	0.560	24.42	4.79	49.00	alum	1.00
116.89	0.000	0.037	0.329	0.634	28.22	7.40	37.88	steel	0.67
139.60	0.000	0.014	0.209	0.777	27.53	7.86	40.25	steel	0.67
144.71	0.000	0.010	0.181	0.809					
159.18	0.000	0.000	0.100	0.900					

Logic Equations
for
Complexity

0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000
139.600	0.000	0.014	0.209	0.777
0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000
144.707	0.000	0.010	0.181	0.809
0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000
139.600	0.000	0.014	0.209	0.777
144.707	0.000	0.010	0.181	0.809
142.153	0.000	0.012	0.195	0.793
	0.000	-0.010	-0.072	0.082
b1 =	0.000	-0.001	-0.005	0.006
bo =	0.000	0.125	0.975	-0.100
	0.00	0.01	0.18	0.81

Table 5-13 New Rolled Component Model

Cost	Very Low	Low	Medium	High	Material	Primary		
					Cost	Cost		
0.000	1.000	0.000	0.000	0.000	0.192	0.004	10.25	alum
0.196	0.914	0.000	0.086	0.000	0.406	0.008	10.50	steel
0.414	0.000	0.387	0.518	0.095	0.475	0.009	11.75	steel
0.484	0.000	0.318	0.556	0.126	0.555	0.007	19.50	alum
0.562	0.000	0.262	0.578	0.160	0.598	0.010	26.25	alum
0.608	0.000	0.236	0.584	0.180	0.637	0.014	18.50	steel
0.651	0.000	0.215	0.586	0.199	1.250	0.017	44.88	alum
1.267	0.000	0.068	0.463	0.469	1.400	0.029	37.88	steel
1.429	0.000	0.051	0.410	0.539	1.450	0.019	49.00	alum
1.469	0.000	0.047	0.396	0.557	1.555	0.031	40.25	steel
1.586	0.000	0.037	0.354	0.608				
2.285	0.000	0.000	0.086	0.914				

Rule 1	0.000	Very Low	0.000
Rule 2	0.000	Low	0.118
Rule 3	0.000	Med	0.181
Rule 4	0.000	High	0.497
Rule 5	0.000		
Rule 6	0.010		
Rule 7	0.118		
Rule 8	0.118		
Rule 9	0.000		
Rule 10	0.010		
Rule 11	0.181		
Rule 12	0.497		
Rule 13	0.000		
Rule 14	0.010		
Rule 15	0.181		
Rule 16	0.385		

Cost Logic Table

Col 1	Col 2	Col 3	Col 4	Col 5	Col 6	Col 7	Col 8	Col 9	Col 10	Col 11	Col 12	Col 13	Col 14	Col 15
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.196	0.914	0.414	0.000	0.000	0.000	0.000	0.000	0.196	0.000	0.414	0.387	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.196	0.914	0.414	0.000	0.651	0.215	1.267	0.068	0.196	0.000	0.414	0.387	1.586	0.354	2.285

Low Cutoff	High Low Cutoff	Low Low Cutoff	High Med Cutoff	Low Med Cutoff	High Cutoff
0.414	1.058	0.262	2.039	0.243	1.332

Cost Calculation
(Center of Gravity Method)

Very Low Cost Contrib	0.0000
Low Cost Contrib	0.1201
Med Cost Contrib	0.4207
High Cost Contrib	1.1183
Very Low Cost Area	0.0000
Low Cost Area	0.1819
Medium Cost Area	0.3686
High Cost Area	0.7439
Estimated Cost =	1.282

For the new rolled component model, the maximum cost is raised to \$2.285 (see Appendix A). The maximum volume and complexity remain at ten percent over the largest component volume and complexity. Table 5-14 shows the new cost estimates for the rolled component set.

Table 5-14 New Cost Estimates for the Rolled Component Set

Component	Volume	Complexity	Actual	Estimated	Deviation	% Deviation	Material
			Cost	Cost			
1	1.722	16.0	\$0.20	\$0.41	-\$0.21	-109.2%	<i>alum</i>
2	1.886	18.2	\$0.41	\$0.49	-\$0.08	-18.6%	<i>steel</i>
3	2.210	20.9	\$0.48	\$0.54	-\$0.06	-11.8%	<i>steel</i>
4	2.963	35.2	\$0.65	\$0.56	\$0.09	13.7%	<i>steel</i>
5	4.978	27.8	\$0.56	\$0.71	-\$0.15	-26.5%	<i>alum</i>
6	5.371	38.9	\$0.61	\$0.73	-\$0.12	-19.2%	<i>alum</i>
7	6.510	139.6	\$1.43	\$1.26	\$0.17	12.0%	<i>steel</i>
8	7.232	144.7	\$1.59	\$1.28	\$0.30	19.2%	<i>steel</i>
9	11.219	105.0	\$1.27	\$1.29	-\$0.03	-2.0%	<i>alum</i>
10	13.016	116.9	\$1.47	\$1.40	\$0.07	5.0%	<i>alum</i>

The estimated costs for the rolled component set range from -2.0 % to -109.2 % of the actual cost. Six components have estimated costs higher than the actual and four have costs lower than the actual. The highest deviation from actual cost still occurs for Component 1. However, the deviation is half of the previous deviation. The deviation is now \$0.21. The smallest deviation from actual cost now occurs for Component 9 instead of Component 4. The deviation is \$0.03. Overall the new rolled model generates estimated costs significantly lower than the original rolled model. In fact if Component 1 were removed from the rolled component set all of the estimated costs would be within 26.5% of the actual cost. The estimated cost of Component 1 is higher because this component has a lower complexity and is also smaller than all the other components.

Component 1 is also made of aluminum. Table 5-14 shows that the smaller aluminum components have higher deviations than the smaller steel components. Thus, components as small as Component 1 with lower complexities should be placed in a separate component set. Although dividing the aluminum and steel into different sets appears to be a possibility, doing this does not yield better cost estimates. The estimated costs are driven primarily by the size and complexity.

For the new extruded component model, the very low volume set contains the smallest volumes 0.566 in³, 1.355 in³ and 1.887 in³. The very low complexity set contains the lowest complexities of 20.5, 21.85 and 24.27. The very low cost set contains the lowest cost of \$0.126. Table 5-15 shows the new model with the additional fuzzy sets.

Table 5-15 New Extruded Component Model

		Volume	Very Low	Low	Medium	High
Volume = Complex =	0.556 20.5	0.000	1.000	0.000	0.000	0.000
		0.556	0.929	0.000	0.071	0.000
		1.355	0.339	0.000	0.565	0.095
		1.887	0.224	0.000	0.613	0.164
		2.989	0.000	0.115	0.580	0.305
		3.778	0.000	0.076	0.518	0.406
		3.961	0.000	0.069	0.502	0.429
		4.406	0.000	0.055	0.459	0.486
		5.176	0.000	0.036	0.379	0.585
		6.108	0.000	0.020	0.276	0.704
		7.102	0.000	0.007	0.162	0.831
7.812	0.000	0.000	0.078	0.922		
Logic Equations for Volume	0.000	0.00	0.000	0.000	0.000	
	0.556	0.93	0.000	0.071	0.000	
	0.000	0.00	0.000	0.000	0.000	
	0.000	0.00	0.000	0.000	0.000	
	0.000	0.00	0.000	0.000	0.000	
	0.000	0.00	0.000	0.000	0.000	
	0.000	0.00	0.000	0.000	0.000	
	0.000	0.00	0.000	0.000	0.000	
	0.000	0.00	0.000	0.000	0.000	
	0.000	0.00	0.000	0.000	0.000	
	0.000	0.00	0.000	0.000	0.000	
	0.000	0.00	0.000	0.000	0.000	
	0.000	0.00	0.000	0.000	0.000	
	0.000	0.00	0.000	0.000	0.000	
	0.000	0.00	0.000	0.000	0.000	
	0.000	0.00	0.000	0.000	0.000	
	0.000	0.00	0.000	0.000	0.000	
	0.000	0.00	0.000	0.000	0.000	
	0.000	0.00	0.000	0.000	0.000	
	0.000	0.00	0.000	0.000	0.000	
	0.556	0.93	0.000	0.071	0.000	
	1.355	0.34	0.000	0.565	0.095	
	0.956	0.63	0.000	0.318	0.0478	
		-0.24	0.000	0.198	0.0381	
	b1 =	-0.74	0.000	0.619	0.1192	
	bo =	1.34	0.000	-0.273	-0.0661	
		0.93	0.00	0.07	0.00	

Table 5-15 New Extruded Component Model

Logic Equations for Complexity

Table 5-15 New Extruded Component Model

Cost	Very Low	Low	Medium	High	Material	Primary
					Cost	Cost
0.000	1.000	0.000	0.000	0.000	0.120	0.006
0.126	0.903	0.000	0.007	0.000	0.291	0.009
0.300	0.000	0.323	0.544	0.133	0.161	0.333
0.337	0.000	0.277	0.562	0.161	0.224	0.406
0.419	0.000	0.204	0.572	0.224	0.421	0.005
0.426	0.000	0.199	0.572	0.229	0.577	0.007
0.584	0.000	0.119	0.531	0.351	0.681	0.010
0.690	0.000	0.085	0.483	0.432	0.791	0.011
0.802	0.000	0.060	0.422	0.518	0.852	0.032
0.884	0.000	0.045	0.374	0.580	0.948	0.036
0.983	0.000	0.031	0.312	0.657		
1.305	0.000	0.000	0.097	0.903		

Rule 1	0.899	Very Low	0.899
Rule 2	0.000	Low	0.101
Rule 3	0.101	Med	0.071
Rule 4	0.000	High	0.000
Rule 5	0.000		
Rule 6	0.000		
Rule 7	0.000		
Rule 8	0.000		
Rule 9	0.071		
Rule 10	0.000		
Rule 11	0.071		
Rule 12	0.000		
Rule 13	0.000		
Rule 14	0.000		
Rule 15	0.000		
Rule 16	0.000		

Cost Logic Table

Col 1	Col 2	Col 3	Col 4	Col 5	Col 6	Col 7	Col 8	Col 9	Col 10	Col 11	Col 12	Col 13	Col 14
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.126	0.903	0.300	0.000	0.000	0.000	0.000	0.000	0.126	0.000	0.300	0.323	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.584	0.119	0.690	0.085	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.126	0.903	0.300	0.000	0.584	0.119	0.690	0.085	0.126	0.000	0.300	0.323	1.305	0.097

Low Cutoff	High Low Cutoff	Low Low Cutoff	High Med Cutoff	Low Med Cutoff	High Cutoff
0.127	0.640	0.181	0.948	0.092	0.126

Cost Calculation
(Center of Gravity Method)

Very Low Cost Contrib	0.0962
Low Cost Contrib	0.0366
Med Cost Contrib	0.0398
High Cost Contrib	0.0001
Very Low Cost Area	0.6434
Low Cost Area	0.0894
Medium Cost Area	0.0766
High Cost Area	0.0002
Estimated Cost =	0.213

For the new extruded component model, the maximum cost is raised to \$1.305 (see Appendix A). The maximum volume and complexity remain at ten percent over the largest component volume and complexity. Table 5-16 shows the new cost estimates for the extruded component set.

Table 5-16 New Cost Estimates for the Extruded Component Set

Component	Volume	Complexity	Actual Cost	Estimated Cost	Deviation	Material	% Deviation
1	0.556	20.50	\$0.13	\$0.213	-\$0.09	<i>steel</i>	-69.0%
2	1.355	24.27	\$0.30	\$0.384	-\$0.08	<i>steel</i>	-28.0%
3	1.887	46.56	\$0.42	\$0.375	\$0.04	<i>steel</i>	10.5%
4	2.989	21.85	\$0.34	\$0.432	-\$0.10	<i>alum</i>	-28.2%
5	3.778	32.07	\$0.43	\$0.497	-\$0.07	<i>alum</i>	-16.7%
6	3.961	163.93	\$0.88	\$0.767	\$0.12	<i>steel</i>	13.2%
7	4.406	184.75	\$0.98	\$0.791	\$0.19	<i>steel</i>	19.5%
8	5.176	49.0	\$0.58	\$0.647	-\$0.06	<i>alum</i>	-10.8%
9	6.108	67.0	\$0.69	\$0.705	-\$0.02	<i>alum</i>	-2.2%
10	7.102	75.7	\$0.80	\$0.740	\$0.06	<i>alum</i>	7.7%

The estimated costs for the extruded component set range from -2.2 % to -69.0 % of the actual cost. Six components have estimated costs higher than the actual and four have costs lower than the actual. The highest deviation from actual cost still occurs for Component 1. However, the deviation is half of the previous deviation. The deviation is now \$0.09. The smallest deviation from actual cost now occurs for Component 9 instead of Component 8. The deviation is \$0.02. Overall the new extruded model generates estimated costs significantly lower than the original extruded model. In fact if Component 1 were removed from the extruded component set all of the estimated costs would be within 28.2% of the actual cost. The estimated cost of Component 1 is higher because this component has a lower complexity and is also smaller than all the other components. Component 1 is made of steel. Table 5-16 shows that the smaller steel

components have higher deviations than the smaller aluminum components. Thus, components as small as Component 1 with lower complexities should be placed in a separate component set. Although dividing the aluminum and steel into different sets appears to be a possibility, doing this does not yield better cost estimates. The estimated costs are driven primarily by the size and complexity.

5.1 Estimating the Cost for the New Models

The costs for the new models are estimated using the same equations shown in Section 4.0. The only difference is that the very low cost sets in the new models are estimated like the low cost sets in the original models and the low cost sets in the new model are estimated like the medium cost sets in the original model. The cost estimate of the medium and large cost sets in the high cost model remain the same. To illustrate the calculation the example shown in Section 4.0 is shown here using the new cost calculation. A volume of 0.556 in³ is the input volume. A complexity of 20.5 is the input complexity.

As in the previous model, the first set of logic equations select the volume and associated memberships that are lower or equal to the input. These equations compare the input number, INPUT, to the volumes in the table. There are two conditions to be met before the logic equation is true. For example, when INPUT is compared to Volume 1 and Volume 2, the first condition is $INPUT \geq \text{Volume 1}$. The second condition is $INPUT < \text{Volume 2}$. If both conditions are true, i.e. INPUT is either equal to or between the two

volumes, then Volume 1 is selected as the lower volume. If both conditions are false or only one condition is true, then neither volume is selected. In the model, a 0.0 is entered if the conditions are not true. The EXCEL formula is:

IF [(INPUT >= Volume 1, INPUT < Volume 2), Volume 1, 0.0].

Thus, when the input volume of 0.556 is compared to Volume 1 = 0.0 and Volume 2 = 0.556, the first condition is true and the second condition is false. Thus, a zero is entered in the logic table.

IF [(0.556 >= 0.0, 0.556 < 0.556), 0.0, 0.0]

The next equation in the logic table compares 0.556 to Volume 2 = 0.556 and Volume 3 = 1.355. For this equation, the first condition is true and the second condition is true. Thus, 0.556 is entered in the logic table.

IF [(0.556 >= 0.556, 0.556 < 1.355), 0.556, 0.0]

For all the other equations in the table, the conditions are false and a 0.0 is entered. Memberships are selected when the volume is selected and are entered in the table when the volume conditions are both true.

The second set of logic equations in the volume logic table select the volume above the

input volume. The EXCEL formula is:

IF [(INPUT <= Volume 1, INPUT < Volume 2), Volume 1=0.0]

Thus, when the input volume of 0.556 is compared to Volume 1 = 0.0 and Volume 2 = 0.556, the first condition is false and the second condition is false. Thus, a zero is entered in the logic table.

IF [(0.556 <= 0.0, 0.556 < 0.556), 0.0, 0.0]

The next equation in the logic table compares 0.556 to Volume 2 = 0.556 and Volume 3 = 1.355. For this equation, the first condition is true and the second condition is true. However, this time 1.355 is entered into the logic table because it is the higher volume. Again, the memberships associated with the volume of 1.355 are entered in the logic table.

IF [(0.556 <= 0.556, 0.556 < 1.355), 1.355, 0.0]

Once the volumes and the associated memberships are selected, a linear regression calculation is used to determine the membership of the input volume in each set. First the average volume and the average membership for each fuzzy set is calculated.

The average volume is $[(0.556 + 1.355) / 2] = 0.956$.

The average membership in the very small fuzzy set is $[(0.929 + 0.339) / 2] = 0.634$.

The average membership in the small fuzzy set is 0.000. The average membership in the medium fuzzy set is $[(0.071 + 0.559) / 2] = 0.315$. The average membership in the large fuzzy set is $[(0.000 + 0.102) / 2] = 0.051$.

The next step is to calculate the estimated regression equation for each membership set.

The form of the estimated regression equation is:

$$y = b_0 + (b_1 * x_{avg}).$$

$$b_1 = \sum ((x_1 - x_{avg}) * (y_1 - y_{avg})) / \sum (x_1 - x_{avg})^2$$

$$b_0 = y_{avg} - (b_1 * x_{avg}).$$

For the very small fuzzy set:

$$x_1 = 0.544$$

$$x_2 = 1.355$$

$$y_1 = 0.929$$

$$y_2 = 0.339$$

$$x_{avg} = 0.956$$

$$y_{avg} = 0.634$$

$$b_1 = \frac{((0.544 - 0.956) + (1.355 - 0.956)) * ((0.929 - 0.634) + (0.339 - 0.634))}{(0.544 - 0.956)^2 + (1.355 - 0.956)^2}$$

$$b_1 = -0.738$$

$$b_o = 0.634 - (-0.738) * (0.956)$$

$$b_o = 1.339$$

$$y = 1.339 - (0.738 * \text{INPUT})$$

$$y = 1.339 - (0.738 * 0.556)$$

$$y = 0.929 \text{ (membership of 0.556 in the small fuzzy set)}$$

For the low fuzzy set:

$$y = 0.000$$

For the medium fuzzy set:

$$x_1 = 0.544$$

$$x_2 = 1.355$$

$$y_1 = 0.071$$

$$y_2 = 0.559$$

$$x_{\text{avg}} = 0.956$$

$$y_{\text{avg}} = 0.315$$

$$b_1 = 0.610$$

$$b_o = -0.268$$

$$y = -0.268 + (0.610 * \text{INPUT})$$

$$y = -0.268 + (0.610 * 0.556)$$

$$y = 0.071 \text{ (membership of 0.556 in the medium fuzzy set)}$$

For the large fuzzy set:

$$x_1 = 0.544$$

$$x_2 = 1.355$$

$$y_1 = 0.000$$

$$y_2 = 0.102$$

$$x_{\text{avg}} = 0.956$$

$$y_{\text{avg}} = 0.051$$

$$b_1 = 0.128$$

$$b_o = -0.071$$

$$y = -0.071 + (0.128 * \text{INPUT})$$

$$y = -0.071 + (0.128 * 0.556)$$

$$y = 0.000 \text{ (membership of 0.556 in the large fuzzy set)}$$

For the input complexity the same type of calculations are performed to determine the membership of the complexity in each complexity fuzzy set. The first set of logic equations select the complexity and associated memberships that are lower or equal to the input. These equations compare the input number, INPUT, to the complexities in the table. There are two conditions to be met before the logic equation is true. For example,

when INPUT is compared to Complexity 1 and Complexity 2, the first condition is $\text{INPUT} \geq \text{Complexity 1}$. The second condition is $\text{INPUT} < \text{Complexity 2}$. If both conditions are true, i.e. INPUT is either equal to or between the two complexities, then Complexity 1 is selected as the lower complexity. If both conditions are false or only one condition is true, then neither complexity is selected. In the model, a 0.0 is entered if the conditions are not true. The EXCEL formula is:

IF [(INPUT $\geq$ Complexity 1, INPUT $<$ Complexity 2), Complexity 1, 0.0]

Thus, when the input complexity of 20.5 is compared to Complexity 1 = 0.0 and Complexity 2 = 20.5, the first condition is true and the second condition is false. Thus, a zero is entered in the logic table.

IF [(20.5 $\geq$ 0.0, 20.5 $<$ 20.5), 0.0, 0.0]

The next equation in the logic table compares 20.5 to Complexity 2 = 20.5 and Complexity 3 = 21.85. For this equation, the first condition is true and the second condition is true. Thus, 20.5 is entered in the logic table.

IF [(20.5 $\geq$ 20.5, 20.5 $<$ 21.85), 20.5, 0.0]

For all the other equations in the table, the conditions are false and a 0.0 is entered. Memberships are selected when the complexity is selected and are entered in the table

when the conditions are both true.

The second set of logic equations in the complexity logic table select the complexity above the input complexity. The EXCEL formula is:

IF [(INPUT <= Complexity 1, INPUT < Complexity 2), Complexity 1=0.0]

Thus, when the input complexity of 20.5 is compared to Complexity 1 = 0.0 and Complexity 2 = 20.5, the first condition is false and the second condition is false. Thus, a zero is entered in the logic table.

IF [(20.5 <= 0.0, 20.5 < 20.5), 0.0, 0.0]

The next equation in the logic table compares 20.5 to Complexity 2 = 20.5 and Complexity 3 = 21.85. For this equation, the first condition is true and the second condition is true. However, this time 20.85 is entered into the logic table because it is the higher complexity. Again, the memberships associated with the complexity of 20.85 are entered in the logic table.

IF [(20.5 <= 20.5, 20.5 < 21.85), 21.85, 0.0]

Once the complexities and the associated memberships are selected, a linear regression calculation is used to determine the membership of the input complexity in each set. First

the average complexity and the average membership for each fuzzy set is calculated.

The average complexity is $[(20.5 + 21.85) / 2] = 21.17$. The average membership in the very low complexity set is $[(0.899 + 0.837) / 2] = 0.868$. The average membership in the low complexity set is 0.000. The average membership in the medium complexity fuzzy set is $[(0.101 + 0.156) / 2] = 0.129$. The average membership in the large complexity fuzzy set is $[(0.000 + 0.007) / 2] = 0.003$.

The next step is to calculate the estimated regression equation for each membership set.

The form of the estimated regression equation is:

$$y = b_o + (b_1 * x_{avg}).$$

$$b_1 = \sum ((x_i - x_{avg}) * (y_i - y_{avg})) / \sum (x_i - x_{avg})^2$$

$$b_o = y_{avg} - (b_1 * x_{avg}).$$

For the very low complexity fuzzy set:

$$x_1 = 20.5$$

$$x_2 = 21.85$$

$$y_1 = 0.90$$

$$y_2 = 0.84$$

$$x_{avg} = 21.17$$

$$y_{avg} = 0.868$$

$$b_1 = \frac{((20.5-21.17) + (21.85-21.17)) * ((0.90-0.87) + (0.84-0.87))}{(20.5 - 21.17)^2 + (21.85 - 21.17)^2}$$

$$b_1 = -0.046$$

$$b_0 = 0.868 - ((-0.046) * (20.5))$$

$$b_0 = 1.837$$

$$y = 1.837 - (0.046 * \text{INPUT})$$

$$y = 1.837 - (0.046 * 20.5)$$

$$y = 0.899 \text{ (membership of 20.5 in the very low complexity fuzzy set)}$$

For the low complexity fuzzy set:

$$y = 0.000$$

For the medium complexity fuzzy set:

$$x_1 = 20.5$$

$$x_2 = 21.85$$

$$y_1 = 0.101$$

$$y_2 = 0.156$$

$$x_{\text{avg}} = 21.17$$

$$y_{\text{avg}} = 0.129$$

$$b_1 = 0.041$$

$$b_o = -0.736$$

$$y = -0.736 + (0.041 * \text{INPUT})$$

$$y = -0.736 + (0.041 * 20.5)$$

$$y = 0.101 \text{ (membership of 20.5 in the medium complexity fuzzy set)}$$

For the large complexity fuzzy set:

$$x_1 = 20.5$$

$$x_2 = 21.85$$

$$y_1 = 0.000$$

$$y_2 = 0.007$$

$$x_{\text{avg}} = 21.17$$

$$y_{\text{avg}} = 0.003$$

$$b_1 = 0.005$$

$$b_o = -0.101$$

$$y = -0.101 + (0.005 * \text{INPUT})$$

$$y = -0.101 + (0.005 * 20.5)$$

$$y = 0.000 \text{ (membership of 20.5 in the large fuzzy set)}$$

Once the memberships are calculated for the volume and complexity fuzzy sets, the rules

determine the “cutoff” memberships. In the fuzzy rule table, the first, second, third and fourth rules compare the very small volume membership to each of the complexity fuzzy set memberships calculated above: very low, low, medium and high. The first four rules are:

Rule 1:	$\text{Min } [0.929, 0.90] = 0.90$	Very low cost fuzzy set
Rule 2:	$\text{Min } [0.929, 0.00] = 0.00$	Very low cost fuzzy set
Rule 3:	$\text{Min } [0.929, 0.10] = 0.10$	Low cost fuzzy set
Rule 4:	$\text{Min } [0.929, 0.00] = 0.00$	Medium cost fuzzy set

The fifth, sixth, seventh and eighth rules compare the low volume membership to each of the complexity fuzzy sets: very low, low, medium and high calculated above. The next four rules are:

Rule 5:	$\text{Min } [0.00, 0.09] = 0.00$	Very low cost fuzzy set
Rule 6:	$\text{Min } [0.00, 0.00] = 0.00$	Low cost fuzzy set
Rule 7:	$\text{Min } [0.00, 0.10] = 0.00$	Low cost fuzzy set
Rule 8:	$\text{Min } [0.00, 0.00] = 0.00$	High cost fuzzy set

The ninth, tenth, eleventh and twelfth rules compare the medium volume membership to each of the complexity fuzzy sets: very low, low, medium and high calculated above. The next four rules are:

Rule 9:	$\text{Min } [0.071, 0.90] = 0.07$	Very low cost fuzzy set
Rule 10:	$\text{Min } [0.071, 0.00] = 0.00$	Low cost fuzzy set
Rule 11:	$\text{Min } [0.071, 0.10] = 0.10$	Medium cost fuzzy set
Rule 12:	$\text{Min } [0.071, 0.00] = 0.00$	High cost fuzzy set

The thirteenth, fourteenth, fifteenth and sixteenth rules compare the large volume membership to each of the complexity fuzzy sets: very low, low, medium and high calculated above. The next four rules are:

Rule 13:	$\text{Min } [0.00, 0.90] = 0.00$	Medium cost fuzzy set
Rule 14:	$\text{Min } [0.00, 0.00] = 0.00$	Medium cost fuzzy set
Rule 15:	$\text{Min } [0.00, 0.10] = 0.00$	High cost fuzzy set
Rule 16:	$\text{Min } [0.00, 0.00] = 0.00$	High cost fuzzy set

The “cutoff” memberships obtained from the rules are then used to obtain the “cutoff” memberships for each cost set. For the very low cost set, the memberships from Rules 1, 2, 5 and 9 are used to find the “cutoff” membership.

Very Low Cost “Cutoff” Membership: $\text{Max } [0.90, 0.00, 0.00, 0.07] = 0.90$

For the low cost set, the memberships from Rules 3, 6, 7 and 10 are used to find the “cutoff” membership.

Low Cost “Cutoff” Membership: $\text{Max } [0.10, 0.00, 0.00, 0.00] = 0.10$

For the medium cost set, the memberships from Rules 4, 11, 13 and 14 are used to find the “cutoff” membership.

Medium Cost “Cutoff” Membership: $\text{Max } [0.00, 0.07, 0.00, 0.00] = 0.07$

For the volume cost set, the memberships from Rules 8, 12, 15 and 16 are used to find the “cutoff” membership.

Large Cost “Cutoff” Membership: $\text{Max } [0.00, 0.00, 0.00, 0.00] = 0.00$

Once the “cutoff” memberships are known for each cost fuzzy set, the logic equations in the cost logic table are used to determine the cost for each “cutoff” membership. The first two columns in the cost logic table are used to find the cost lower than the cutoff cost of the very low cost fuzzy set. The second two columns in the cost logic table are used to find the cost higher than the cutoff cost of the very low cost fuzzy set.

For the very low cost fuzzy set, a membership of 0.899 is used. The logic equation is the same as the logic equations used in the volume and complexity logic tables. However, this time the “cutoff” membership calculated by the rules is the input. Thus, the first equation compares 0.899 to the first very low cost membership in the cost table and the second very low cost membership in the cost table. The first condition is true and the

second condition is false. Thus, the first input in Column 1 and 2 is 0.0 for the cost and 0.0 for the membership.

IF $[(0.899 < 1.0, 0.899 \geq 0.903), 0.0, 0.0]$

The second equation compares 0.899 to the second very low cost membership and the third very low cost membership in the cost table. For this equation, the first condition is true and the second condition is true. Thus, the second input in the table is \$0.126 for the cost and 0.903 for the membership, Column 1 and 2, respectively.

IF $[(0.899 < 0.903, 0.899 \geq 0.00), 0.126, 0.0]$

All other inputs in the first two column of the logic table are 0.0. In the second two columns of the first section, the first equation compares 0.899 to the first very low cost membership and the second very low cost membership in the cost table. For these equations, the first condition is false and the second condition is false. The membership is 0.0 and the cost is \$0.0. The next set of equations, compare the second very low cost membership and the third very low cost membership in the cost table. For these equations, the first condition is true and the second condition is true. The membership is 0.00 and the cost is \$0.30.

In the second section of the cost logic table, the cutoff costs are found for the low cost fuzzy set. The low cost fuzzy set is now trapezoidal in shape. Thus, two costs must be

determined for the cutoff membership. There are four sets of equations used to determine the cutoff costs. Columns 5 and 6 find the cost lower than the cutoff cost on the high cost side of the trapezoid. Columns 7 and 8 find the cost higher than the cutoff cost on the high cost side of the trapezoid. Columns 9 and 10 find the cost lower than the cutoff cost on the low cost side of the trapezoid. Columns 11 and 12 find the cost higher than the cutoff cost on the low cost side of the trapezoid. For the low cost fuzzy set, a membership of 0.10 is used. For Columns 5, 6, 7 and 8, the logic equation is the same as the logic equations used in Columns 1, 2, 3 and 4. However, the conditions are reversed in Columns 9, 10, 11 and 12. These equations find the cost on the low cost side of the trapezoid. The new equation is:

IF [(cutoff $\geq$ Membership 1, cutoff $<$ Membership 2), Membership 1, 0.0]

In the third section of the cost logic table, the cutoff costs are found for the medium cost fuzzy set. The medium cost fuzzy set is still trapezoidal in shape. Thus, two costs must be determined for the cutoff membership. There are four sets of equations used to determine the cutoff costs. Columns 13 and 14 find the cost lower than the cutoff cost on the high cost side of the trapezoid. Columns 15 and 16 find the cost higher than the cutoff cost on the high cost side of the trapezoid. Columns 17 and 18 find the cost lower than the cutoff cost on the low cost side of the trapezoid. Columns 19 and 20 find the cost higher than the cutoff cost on the low cost side of the trapezoid. For the medium cost fuzzy set, a membership of 0.07 is used. For Columns 13, 14, 15, 16, 17, 18, 19 and 20, the logic equations are the same as the logic equations used in Columns 5, 6, 7 8, 9,

10, 11 and 12.

In the fourth section of the cost logic table, the cutoff costs are found for the high cost fuzzy set. For the high cost fuzzy set, only one cutoff cost is required. Thus, there are two set of equations used to determine the cutoff cost. Columns 20, 21, 22 and 23 find the membership and the cost for the high cost fuzzy set. For the high cost fuzzy set, the same equations used for the very low cost fuzzy set are used with reversed conditions.

Once the costs above and below the cutoff memberships are determined, the spreadsheet calculates the cost at the cutoff membership. For the very low cost fuzzy set in the extrusion example, the membership above the “cutoff” membership is 0.903 and the cost is \$0.126 and the membership below the “cutoff” membership is 0.0 and the cost is \$0.300. To find the cutoff cost at the cutoff memberships, a linear interpolation is made between the memberships and the costs. The formula used to calculate the cost is:

$$C_{\text{cutoff}} = C_A - [(C_A - C_B) / (M_A - M_B) * (M_A - M_{\text{cutoff}})]$$

Where

C_A is the cost above the “cutoff” membership

C_B is the cost below the “cutoff” membership

M_A is the membership above the “cutoff” membership

M_B is the membership below the “cutoff” membership

M_{cutoff} is the “cutoff” membership

$$C_{\text{cutoff}} = \$0.126 - ((\$0.126 - \$0.30) * (0.903 - 0.899) / (0.903 - 0.00))$$

$$C_{\text{cutoff}} = \$0.127$$

For the low cost fuzzy set in the extrusion example, the membership above the “cutoff” membership is 0.085 and the cost is \$0.69. The membership below the “cutoff” membership is 0.119 and the cost is \$0.584. To find the cutoff cost, a linear interpolation is made between the memberships and the costs. This interpolation provides the cost on the high side of the low cost trapezoid.

$$C_{\text{cutoff}} = C_A - [(C_A - C_B) / (M_A - M_B) * (M_A - M_{\text{cutoff}})]$$

$$C_{\text{cutoff}} = \$0.69 - ((\$0.69 - \$0.584) * (0.119 - 0.10) / (0.119 - 0.085))$$

$$C_{\text{cutoff}} = \$0.640$$

For the cost on the low side of the low cost trapezoid, the membership below the “cutoff” is 0.00 and the cost is \$0.126. The membership above the “cutoff” membership is 0.323 and the cost is \$0.300. To find the cutoff cost, a linear interpolation is made between the memberships and the costs.

$$C_{\text{cutoff}} = C_A - [(C_A - C_B) / (M_A - M_B) * (M_A - M_{\text{cutoff}})]$$

$$C_{\text{cutoff}} = \$0.30 - ((\$0.30 - \$0.126) * (0.323 - 0.10) / (0.323 - 0.00))$$

$$C_{\text{cutoff}} = \$0.181$$

For the medium cost fuzzy set, the membership above the “cutoff” membership is 0.097 and the cost is \$1.305. The membership below the “cutoff” membership is 0.00 and the cost is \$0.00. To find the cutoff cost, a linear interpolation is made between the memberships and the costs. This interpolation provides the cost on the high side of the medium cost trapezoid.

$$C_{\text{cutoff}} = C_A - [(C_A - C_B) / (M_A - M_B) * (M_A - M_{\text{cutoff}})]$$

$$C_{\text{cutoff}} = \$1.305 - ((\$1.305 - \$0.0) * (0.097 - 0.071) / (0.097 - 0.00))$$

$$C_{\text{cutoff}} = \$0.948$$

For the cost on the low side of the low cost trapezoid, the membership below the “cutoff” is 0.00 and the cost is \$0.00. The membership above the “cutoff” membership is 0.097 and the cost is \$0.126. To find the cutoff cost, a linear interpolation is made between the memberships and the costs.

$$C_{\text{cutoff}} = C_A - [(C_A - C_B) / (M_A - M_B) * (M_A - M_{\text{cutoff}})]$$

$$C_{\text{cutoff}} = \$0.126 - ((\$0.126 - \$0.00) * (0.097 - 0.071) / (0.097 - 0.00))$$

$$C_{\text{cutoff}} = \$0.092$$

For the high cost fuzzy set in the extrusion example, the membership below the “cutoff” membership 0.0 and the cost is \$0.126. The membership above the “cutoff” membership is 0.133 and the cost is \$0.300. To find the cutoff cost a linear interpolation is made between the memberships and the costs.

$$C_{\text{cutoff}} = C_A - [(C_A - C_B) / (M_A - M_B) * (M_A - M_{\text{cutoff}})]$$

$$C_{\text{cutoff}} = \$0.126 - ((\$0.126 - \$0.300) * (0.0 - 0.0) / (0.0 - 0.133))$$

$$C_{\text{cutoff}} = \$0.126$$

The estimated cost for the extrusion example is calculated using the cutoff cost (CC), the cutoff membership (CM) and the maximum cost (MC). First, the areas are calculated using the cutoff costs calculated above.

The area of the very low cost fuzzy set is:

$$\text{Low Cost Area} = (CM * CC) + (0.5 * CM * (MC - CC))$$

$$\text{Low Cost Area} = (0.899 * \$0.127) + (0.5 * 0.899 * (\$1.305 - \$0.127))$$

$$\text{Low Cost Area} = \$0.6434$$

The area of the low cost fuzzy set is:

$$\text{Low Cost Area} = CM * ((MC + (\text{High Side Cutoff Cost} - \text{Low Side Cutoff Cost})) * 0.5$$

$$\text{Low Cost Area} = (0.10 * (\$1.305 + (\$0.640 - \$0.181))) * 0.5$$

$$\text{Low Cost Area} = \$0.0894$$

The area of the medium cost fuzzy set is:

$$\text{Medium Cost Area} = CM * ((MC + (\text{High Side Cutoff Cost} - \text{Low Side Cutoff Cost})) * 0.5$$

$$\text{Medium Cost Area} = (0.071 * (\$1.305 + (\$0.948 - \$0.092))) * 0.5$$

$$\text{Medium Cost Area} = \$0.0766$$

The area of the high cost fuzzy set is:

$$\text{High Cost Area} = (\text{CM} * \text{MC}) + (0.5 * \text{CM} * \text{CC})$$

$$\text{High Cost Area} = (0.00035 * \$1.305) + (0.5 * 0.00035 * \$0.126)$$

$$\text{High Cost Area} = \$0.0002$$

The contributions for each of the cost sets are a function of the area, the cutoff cost [CC] and the maximum cost [MC].

The very low cost contribution (VLCC) for the very low cost fuzzy set is:

$$\text{VLCC} = \frac{[\text{CC}^2 * 0.5] + [[\text{CC} + [[\text{MC} - \text{CC}] * 1/3] * 0.5 * [\text{MC} - \text{CC}]] * [\text{Very Low Cost Area}]]}{[\text{CC} + [\text{MC} - \text{CC}] * 0.5]}$$

$$\text{VLCC} = \frac{[\$0.127^2 * 0.5 + [[\$0.127 + [\$1.305 - \$0.127] * 1/3] * 0.5 * [\$1.305 - \$0.127]] * 0.6434}{[\$0.127 + [\$1.305 - \$0.127] * 0.5]}$$

$$\text{VLCC} = \$0.0962$$

The low cost contribution (LCC) for the low cost fuzzy set is:

$$\text{LCC} = [\text{High Cutoff Cost} + \text{Low Cutoff Cost}] / 2 * [\text{Medium Cost Area}]$$

$$\text{LCC} = [\$0.640 + \$0.181] / 2 * \$0.0894$$

$$\text{LCC} = \$0.0366$$

The medium cost contribution (MCC) for the medium cost fuzzy set is:

$$MCC = [\text{High Cutoff Cost} + \text{Low Cutoff Cost}] / 2 * [\text{Medium Cost Area}]$$

$$MCC = [\$0.948 + \$0.092] / 2 * \$0.0766$$

$$MCC = \$\$0.0398$$

The high cost contribution for the high cost fuzzy set is a function of the maximum cost (MC), the high cutoff cost (HCC) and the low medium cutoff cost (LMCC).

$$\frac{[(MC-HCC) * (MC+HCC)/2] + [(LMCC + [(HCC-LMCC) * 2/3]/2 * (HCC-MCC)) * LCA]}{[(MC-HCC) + (HCC-LMCC) * 0.5]}$$

$$\frac{[(1.305-0.126) * (1.305+.126)/2] + [(0.092 + [(0.126-0.092) * 2/3]/2 * (0.126-0.092))] * 0.0002}{[(1.305-0.126) + (0.126-0.092) * 0.5]}$$

$$\text{High Cost Contribution} = \$\$0.0001$$

The estimated cost is the sum of the contribution divided by the sum of the areas.

$$\text{Estimated Cost} = \frac{(\$\$0.0962 + \$\$0.0366 + \$\$0.0398 + \$\$0.0001)}{\$0.6434 + \$0.0894 + \$0.0766 + \$0.0002}$$

$$\text{Estimated Cost} = \$0.213$$

5.2 Validation of the Fuzzy Cost Models

To validate the five fuzzy cost models three components made from each process are randomly selected. Table 5-17 shows the results for each of the components. The new fuzzy cost models with four fuzzy sets are used to estimate the cost. The results show that the stamped component model estimates the cost within 20.7 % of actual. The small injection molded model estimates the cost within 18 % of actual. The large injection molded model estimates the cost within 44.8 % of actual. The large injection molded model needs to be split into more fuzzy sets to obtain better cost estimates. The rolled component model estimates the cost within 32.2 % for the two steel components. The estimate for the aluminum component is within 6.1 %. This result suggests that the two types of components be split into separate sets. The extruded model estimates the cost within 41.2 % for the steel component and 10.6 % for the aluminum component. This result also suggests that the two types of components be split into separate sets.

Table 5-17 Model Validation of the Fuzzy Sets

Component	Processes	Volume	Complexity	Actual Cost	Estimated Cost	Deviation	% Deviation
1	Stamp	0.442	31.2	\$0.105	\$0.109	-0.004	-3.8 %
2	Stamp	0.552	48.9	\$0.158	\$0.125	0.033	20.9 %
3	Stamp	0.663	71.3	\$0.188	\$0.156	0.032	17.0 %
4	Small Inject Mold	0.331	27.4	\$0.039	\$0.046	-0.007	-17.9 %
5	Small Inject Mold	0.497	48.1	\$0.052	\$0.059	-0.007	-13.5 %
6	Small Inject Mold	0.773	59.2	\$0.073	\$0.067	0.006	8.2 %
7	Large Inject Mold	9.067	44.2	\$0.757	\$0.893	-0.136	18.0%
8	Large Inject Mold	10.601	52.9	\$0.877	\$1.27	-0.393	44.8 %
9	Large Inject Mold	14.134	56.8	\$1.152	\$1.56	-0.408	35.1 %
10	Roll (AL)	5.30	47.0	\$0.59	\$0.75	-0.16	-27.1 %
11	Roll (AL)	8.834	67.2	\$0.98	\$1.04	-0.06	-6.1 %
12	Roll (Steel)	9.367	157.2	\$2.02	\$1.37	0.65	32.2 %
13	Extrude (Steel)	4.184	113.1	\$0.90	\$0.66	0.24	26.7 %
14	Extrude (Steel)	6.087	147.3	\$1.31	\$0.77	0.54	41.2 %
15	Extrude (Alum)	7.601	84.5	\$0.85	\$0.76	0.09	10.6 %

6.0 Additional Research

The next step in this research would be to expand the data sets with additional components. Adding additional components may help with the estimation of the smaller components. Another approach may be to increase the number of volume and complexity fuzzy sets. Once these tasks are performed, additional components may be added for other processes. Additional materials should also be evaluated to make this a good cost-estimating tool.

Another idea would be to set up a fuzzy logic cost model to estimate the cost for a group of products. The model would also be based on the size and complexity. However, the complexity could actually be based on the number of components that are required to make the product, the number of processes and materials required to make the components. This type fuzzy cost model could be used to estimate the cost of potential new products of similar design very quickly.

7.0 References

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Appendix A

The estimated costs for the component sets are dependent on the maximum cost selected. Thus, arbitrarily setting the maximum cost to ten percent higher than the largest component cost does not produce the desired cost estimation result. Therefore, a new method was developed. The method developed must be used after the fuzzy costs are determined

The method used is:

- 1) Set the maximum cost to ten percent higher than the highest cost component.
- 2) Calculate the estimated costs for each component using a maximum cost ten percent higher than the largest component's cost.
- 3) Subtract the estimated cost from the actual cost to determine the variance.
- 4) Calculate the average variance for the component set.
- 5) Change the maximum cost by the variance.
- 6) Recalculate the estimated costs and repeat Step 3 and 4.
- 7) Iterate until the average mean is at least 0.00

Using the above method, the maximum cost for the stamped component set is \$0.255. The maximum cost for the small injection molded component set is \$0.086. The maximum cost for the large injection molded component set is \$6.83. The maximum cost for the rolled component set is \$1.82 and the maximum cost for the extruded component set is \$1.12.