A Methodology for Determining Engineering Costs and Their Effects on the Development of Product Families

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Abstract

The goal of most firms is to deliver products that satisfy customer needs. Delivering a variety of *differentiated* products allows firms to satisfy the broadest range of customers. There is, however, a fundamental tension between this product differentiation and product cost. The use of product platforms allows a firm to reduce this tension, offering variety while also benefiting from the economics of mass production for shared components. The selection of components and subassemblies for platforming can have wide ranging effects on both product performance and cost. This thesis addresses the latter by presenting a methodology to assess product development costs, the amount of part sharing in a product family, and the effects of platforming on development, fabrication, and assembly costs for product families.

Ordinal metrics are presented to assess the performance of product families. The methodology of process-based cost modeling, used to estimate product fabrication and assembly costs, is also posed. A method for determining the allocation of costs for parts and subassemblies shared among product family variants is outlined.

A process-based cost model of the automotive product development process is presented. This model uses product part and subassembly characteristics to estimate the engineering effort required at various stages of the development process. Product development cycle time is also estimated. Linear regression analysis is used to determine which part and subassembly characteristics affect engineering effort. Additional development costs, such as computer hardware and software, overhead, and physical prototypes are also taken into account.

Two automotive body architectures are analyzed to determine the cost savings from platforming: a tubular architecture (low tooling cost; high variable costs) and a traditional unibody architecture. Of the two designs, the tubular architecture is found to have less cost savings from platforming, even though the tubular architecture shares more parts. The higher fraction of variable costs and lower tooling cost, reduce the opportunity for sharing in the tubular architecture.

Two instrument panel (IP) beam designs are also compared to study the effects of parts consolidation. A magnesium die cast IP beam is compared to a functionally equivalent steel IP beam that contains over six times as many parts. Development costs are found to make parts consolidation an attractive option, while this consolidation is found to reduce the opportunity for sharing and thus cause the magnesium IP beam family to be a more costly option than the steel design.

Across all case studies, the fabrication and assembly of products are found to account for the majority of product cost; the majority of cost savings from platforming however, come from reduced development and assembly costs. Additionally, production volume and product lifetime are found to have large effects on which product architecture performs better. A significant perspective result, which emerged, was that the part sharing metric weighted by fabrication investment is found to be the most effective predictor of cost savings of the metrics tested.

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1. Introduction

The goal of most firms is to deliver products that satisfy customer needs. Firms can pursue two types of competitive advantage; they can be low cost and/or provide differentiation. There is, however, a fundamental dichotomy between cost and differentiation [1]. Traditionally, low cost has been achieved through mass production. Mass production provides economies of scale by producing a large number of nearly identical products and thus reduces product cost. Nonetheless, variety is critical to a firm's product offering [2]. In the early days of the U.S. automobile industry Ford and General Motors had very different product strategies. Ford concentrated on the Model T, while GM produced five product models to accommodate buyers at different stages of their lives. Ford and the Model T lost market share to GM's wider range of products [3]. However this product variety can increase production costs and makes the firm more complex; the costs of this complexity are real and significant [4, 5]. One way in which the tension between product differentiation and product cost can be relieved is through the use of product platforms. A product platform is a set of subsystems from which derivative or variant products can be developed and manufactured [6]. These variant products combine both shared and unique components to perform a given function. The use of product platforms allows a firm to offer differentiated products while also benefiting from the mass production of shared components.

The use of product platforms can give a firm a strategic advantage in the market place. Sony's use of a platform strategy in addition to its flexible manufacturing allowed the company to target certain niche segments of the Walkman market that were deemed too small to be profitable by its competitors. This increased the longevity of Sony's products and allowed them to charge higher prices (a premium of over $15 for their "sport" model) [7]. There are however some drawbacks to the sharing of parts for a family of products. Integral designs that have custom systems that are not shared throughout the product family perform better on a material cost or mass basis [8]. In some cases a shared component or subassembly will be overdesigned for certain variant products. This overdesign cost can be significant in high production volume cases [9].

Determining the cost benefits and drawbacks of alternative strategies for any development project is important, but this is especially true for a family of products.

It is believed that while the product development process accounts for a relatively small amount of the total cost of the development effort, between 70% and 90% of total costs are determined during the early stages of the development process [10, 11]. Design choices such as which materials are used in a product can affect the manufacturing process that will be used to fabricate the constituent parts of the finished product as well as the number of parts required. These decisions can also affect the performance of the product, the cost of the product, and lead time of the development project. These are all important factors that will determine the product's success or failure. With respect to product families, certain manufacturing technologies are more amenable to part sharing than others, therefore if a portfolio of products is being developed, the ability to share parts between members of the product family must also be considered. The choice of a material and manufacturing technology can have significant effects throughout the development process. It is important to make well-informed decisions about which parts will be shared and which technologies will be used to facilitate this sharing. While these decisions should be based on both cost and revenue estimations for various strategies, this work focuses on the development of a cost estimation tool that can be used in the early stages of the product development process to make product family decisions and select manufacturing technologies. This tool will compare cost and lead time for various product families and numerous manufacturing technologies. The importance of product family design, manufacturing technology choice, manufacturing costs, and development costs are explained in the following sections.

1.1 Background

1.1.1 Product Platforms and Parts Sharing

As mentioned above, a product platform is a set of subsystems from which derivative or variant products can be developed and manufactured [6]. These variant products combine both shared and unique components to perform a given function. The product family is the group of variants that are derived from a given platform [8]. There are two methods in which a product family can be designed. The *a priori* method involves designing the entire product family from the top down. The *a posteriori* method involves taking a previously designed product and making changes to that product to produce other variant products [12]. The time reduction and cost savings derived from a product family approach *vis a vis* an individual product approach depends on both product characteristics as well as the engineering effort required for the project and the development project lead time.

Benefits of the platform approach include reduced manufacturing cost and development time. Decreased manufacturing cost is due to the increased number of units over which fixed costs are spread for parts that are shared in the product family [9, 13]. In the automobile industry, the sharing of underbodies can lead to a 50% reduction in capital investment [13]. One manufacturer reduced its workforce by 35% by standardizing some materials to the highest specifications in the product range; this more than made up for the increased material costs [5]. The reuse of subassemblies and components can reduce the cost of design as well as the time required to bring variant products to market [8, 9, 13]. Reuse of ready-made solutions can also reduce technological risk [14, 15]. From an operational standpoint the use of shared parts can also lead to reduced holding costs and work in process [16]. Proper design of a product family can have significant technological and economic advantages [12].

As mentioned above, there can also be drawbacks to the use of a platform strategy. The requirement that parts be shared throughout the product family may constrain the design and may cause some difficulties in coordination [14]. There is also the possibility of lost revenue due to lower perceived quality in products with shared parts [8, 9, 17]. Desai, et al., propose that when determining which components to share for a product family both cost and revenue implications should be noted; even well hidden shared parts can lower perceived value in consumer products [18]. These negative aspects of part sharing for a product family must be compared with the benefits outlined above to determine the proper strategy for the product family.

To better understand product portfolio strategies and determine the trade-offs that need to be made between competing options, some method of measuring the degree of part sharing within a family of products is needed. In addition to being an important metric in and of itself, this measure can also be used to determine the effects of commonality on other performance measures. Collier proposes a commonality index that relates the average number of parent items per average distinct component part. It is shown that total cost decreases substantially with higher degrees of commonality [19]. Guerrero uses Collier's commonality index and shows that high commonality product structures are less cost sensitive to production strategy given unknown demand [20]. Jiao and Tseng add production volume and cost of component parts to Collier's commonality index and suggest that high cost uncommon parts should be avoided [21]. Wacker and Treleven propose an ordinal measure of part commonality as well as suggesting different types of part commonality that can be measured. These types include total commonality (an ordinal version of Collier's commonality index), within product commonality, between product commonality, and incremental commonality (similar to between product commonality, but measures the percentage of new uncommon components) [22]. Tsubone, et al., describe part commonality as ratio of finished product varieties to the number of part item varieties. A measure of process commonality is also proposed; this metric, defined as the process flexibility factor, is computed by determining the number of processes that a component can be processed by and summing over the entire set of components. These measures are then used to determine the effects of component part commonality on buffer size and workload imbalance [23]. Thomas defines commonality as the number of unique components in a system relative to the total number of system components. Excess functionality is then shown to increase as the number of unique parts is decreased (given that component requirements for the system do not change) [24]. As mentioned above, this excess functionality and its cost must be compared to the benefits of sharing parts. Several measures of part sharing have been proposed and shown to be a valuable tool in assessing portfolio strategies. A part sharing measure for use in this thesis is proposed in Section 2.1.3.

1.1.2 Parts Consolidation and Manufacturing Strategy

Different operating scenarios and product performance goals necessitate different manufacturing technology and material combinations. When developing a family of products, other considerations should be taken into account in addition to part sharing.

Hu and Poli compare injection molding and stamping for functionally equivalent products. They find stamped products to be preferable at higher production volumes in both the cost [25] and time to market perspectives [26]. Jain shows that for a similar body architecture an aluminum structure is more expensive to manufacture and assemble than its steel counterpart at a given production volume [27]. This may explain aluminum's use in high-end automobiles where performance can command a price that offsets the increased cost. Manufacturing technology decisions must take several factors into account.

Design for manufacturing and assembly is a methodology that recommends reducing the number of parts in a design to the least number possible. It is posed that the simplification that arises from reducing the number of parts improves the product [28]. Ernst proposes that reducing the number of parts in a product will result in cost savings. IBM increased productivity by 700% after reducing part count by two-thirds; Ford reduced the part count in its door trim by 79%, assembly cost by 94%, and material costs by 27% [29]. Plastics and composites such as reaction injection molding and are thought to offer weight savings as well as the ability to consolidate parts and thus reduce the part count [30, 31]. The use of resin transfer molding to replace an aluminum sheet metal design resulted in over 700 fewer holes needed, reduced part weight, and a 30% cost reduction [32]. The part consolidating benefits of both magnesium die casting [33] and hydroforming are also proffered [34]. However, the more complex parts required for part consolidation efforts can require longer lead times [35]. Alternative manufacturing processes can also have longer process cycle times and lack the knowledge base of more conventional processes [34]. Kang shows that composite intensive automotive bodies with as few as eight major parts are cost competitive with steel bodies at low (less that 25,000 per year) production volumes. However, the long cycle times required for the component parts of these vehicles make them less competitive at higher production volumes [36]. The choice of a manufacturing technology greatly influences the amount of part consolidation that can be achieved. Any benefits of part consolidation should be compared to possible increased cost or increased lead time, and the ability to share parts with other variants in the product family, and those resulting cost savings.

The choice of manufacturing technology choice can have wide ranging and dramatic effects on cost, development effort, and lead time. Ward, et al., empirically demonstrate the relationship between process choice and competitive priorities. These priorities include cost, quality, lead time, and flexibility [37]. Cost and lead time will be discussed in the following sections. Quality is viewed as an independent variable, the discussion of which is beyond the scope of this work. The added competitive dimension of flexibility increases the importance of manufacturing technology choice [38]. Sony's advantages in the Walkman market were due to both their use of product families and their flexible manufacturing strategies [7]. In addition to allowing a company to tap into certain market niches, flexibility can also allow a firm to respond to changes in market demand. In the automobile industry the time period between when tooling and capacity requirements are determined and when actual production begins can be up to three years; the difference between sales forecasts made at this time and actual demand is about ± 40% [39]. Flexibility can have various meanings. Manufacturing literature contains over fifty different terms for various types of flexibility [40]. Lavington views flexibly as being useful to mitigate the "risk that arise from the immobility of invested resources" [40, 41]. The risk reducing benefits of product families has been discussed in preceding sections. Sethi and Sethi describe production flexibility as the ability of a manufacturing system to produce a large number of part types without major capital equipment investment. This type of flexibility works in concert with part families in allowing the firm to reduce risk [40]. A firm's competitive priorities, ability to respond to market demand, and product family are all affected by manufacturing technology choice. These alternative strategies need to be assessed and trade-offs made between them. Explicit early-stage decision making tools to assist in making these trade-offs are needed. Previous research relating to the estimation of these quantities is discussed in the following two sections.

1.1.3 Cost Modeling

As mentioned above, it is believed that while the product development process accounts for a relatively small amount of the total cost of the development effort, between 70% and 90% of total costs are determined during the early stages of the development process

[10, 11]. In some cases the decisions made in the early stages of the product development process can lead to and affect billion dollar investments. Ulrich and Pearson analyze the manufacturing costs of various coffee makers and observe that there is no significant relationship between either aesthetics or ergonomics and manufacturing cost [42]. So while the goal of designing the best product and achieving the lowest cost are often at odds [43], high manufacturing cost is neither a necessary or sufficient condition for product success (as determined by the consumer's perceived value). Engineering high cost products does not guarantee that customers will pay high prices, so products should be designed for minimum cost, while meeting performance requirements. The importance of reliable cost information in the development stage cannot be overstated. Product strategies based on faulty cost assumptions will most likely fail in the marketplace [44]. It is estimated that over half of development efforts end up being financial failures [45]. In the mid 1970's one US automobile company spent considerable time and resources developing an electronic fuel injection system only to determine later that is was too expensive to be commercially viable [46]. The ability to accurately predict costs at each stage of a development effort has been described as being at the core of competitive manufacturing [47]. Companies such as Harley-Davidson have used cost modeling to gain a competitive advantage and better interact with their suppliers [48]. Cost estimation tools can allow development engineers to determine the commercial viability of various designs as well as compare alternative designs based on cost. A well-developed cost analysis tool can have dramatic effects on the development process. A group using a computer based cost analysis system designed products in 30% less time and at 40% less cost than their counterparts using conventional methods [49].

The goal of cost modeling is to determine the cost of a process or product before it has been executed or produced. There are two widely recognized methods of cost estimation. Variant cost estimation uses similarities between the current product or process being studied and previous products or processes that have been completed to determine costs. Generative cost estimation determines costs based on required production operations [50]. Asiedu and Gu refer to these two methods as analogous models and parametric models respectively [51]. The fact that variant based costing relies on previous products makes it less useful for new technologies or novel products. One form of variant based costing for a machined part, from Daschbach, is shown in Equation 1-1 [52]. This equation determines manufacturing costs based on a regression relating the costs of previous parts to weight, the tolerances required, the number of parts, and a calibrating factor. This method relies on the parts for which costs are being determined having characteristics close to those for on which the regression is based. Marx, et al., detail a variant cost model which determines the cost of an aircraft wing relating cost to historical data about labor, materials, learning curve effects, production quantity, and lot size.

$$Cost = K_D \times (weight)^{0.92} \times (tolerance)^{-1.4} \times (number\_of\_parts)^{1.1} \tag{1- 1}$$

Several generative models have also been proposed for use in cost estimation of both manufacturing and assembly. Leibl, et al., pose a model for sheet metal based designs; this model can be used at various stages of development and compares various joining solutions to determine manufacturing costs [49]. Shehab and Abdalla use *if / then* statements to determine a machining process. Set-up time, run time, and material usage are then calculated based on the part and process characteristics to estimate manufacturing cost [11]. Noble and Tanchoco use machine cost, the variable cost of a given process, and material cost to determine the total cost of a shield for an electrical metering device [43]. Wei and Egbelu estimate machining cost based on the amount of material removed, the type of fixture used, and set-up costs. Boothroyd, et al., propose a method for determining the labor portion of assembly cost based on data obtained from observing the time various subjects required to complete certain tasks. The tasks required for the assembly of the product in question and this data are then used to generate a cost for the assembly [28]. Although there are many cost models available for various processes there doesn't seem to be a widely accepted and used system [47].

Field, et al., and Noble and Tanchoco lament the divorce of the cost estimation process from the design process. This can either cause cost to be a constraint that the designer must design to, thus limiting options, or cost estimation is performed at a later stage and can cause designs to be reworked [43, 53]. Since correcting a design is more costly than correctly designing a product in the first place, an early stage cost estimation tool that can provide accurate costing data is essential [47]. Allowing the designer to establish the relationship between cost and design decisions is the most important function of a cost estimation tool. A valuable cost estimation tool would consider all aspects of a products life, from development until disposal [51]. This would allow the designer to make explicit trade-offs between certain features or product characteristics and their marginal cost. Noble and Tanchoco suggest that a cost estimation tool should analyze and present quantifiable information, allow the decision maker to process or integrate uncertain or incomplete information throughout the design process, and allow the designer to be the decision maker that drives the design process [43].

The ability to trace costs to certain cost drivers is of paramount importance in the design process. Like the backward looking process of activity-based costing, cost estimation models should trace costs to certain activities and processes. Activity based costing looks at the range of activities required to deliver a product and assigns the cost of these activities to the range of products that the company manufactures based on the product's usage of these activities. The future of activity based costing is said to be predictive capability that allows decision makers to determine the resources needed for future products [54]. The benefits of activity-based costing have been shown in many situations. Cooper and Kaplan discuss a valve company that was losing money on 75% of their products; activity based costing was used to determine which products were profitable and should be kept or expanded and which should be dropped [55]. Cleland shows how the adoption of activity based costing allowed a manufacturing company to go from making significant loses to significant profits [56]. Angelis and Lee demonstrate that activity based costing can be used in a strategy framework to determine the best investment alternatives [57]. In addition to increased profitability, activity based costing allows decision makers the ability to identify the best opportunities for improvement and learning [58]. A useful cost estimation tool would include all of the benefits that can be accrued from activity based costing as well as the predictive ability to allow designers to make early stage trade-offs based on this information.

Technical or process-based cost modeling (PBCM) is a generative cost estimation technique. PBCM analyzes the economics of manufacturing by relating component characteristics (i.e. wall thickness) to engineering and manufacturing quantities (press size). These quantities are then used to determine the manufacturing costs of the component. PBCM can be used to determine manufacturing cost early in the design process [59]. PBCM breaks down the manufacturing costs for several manufacturing processes into detailed elements of both fixed and variable cost categories. PBCM fulfils most of the requirements set forth above and is detailed further in section 2.1.

1.1.4 Product Development Cost and Lead Time Modeling

Product development is the set of activities that takes a concept for satisfying perceived needs and transforms it into a product that is ready for the market. For some complex products, such as automobiles the product development process can take years and require millions of man-hours of effort [60]. The product development process consists of the activities required to go from concept development to process specification to pilot production.[1] Concept development is the first stage of the product development process. At this stage a market opportunity has been defined and a concept for the product is proposed and approved. Next is the product planning phase, this is the phase in which product layout as well as cost and performance targets are specified. During the advanced and product engineering phases, product components (such as engines or control systems) are developed and detailed designs of the various parts of the product are produced. Next, the product is prototyped and tested. Finally, the manufacturing and assembly processes are specified during the process engineering phase.

Ideal product development efforts produce quality products at reduced cost while decreasing development time, cost, and adding development capability [61]. Rosenau finds that among product development professionals the most important product development goal is product performance. The importance of performance is followed by product cost, the development schedule, and development project cost [62, 63]. Datar, et al., and Hall and Jackson show the importance of product development process speed in determining the commercial success of products [64, 65]. The process of developing products is a complex set of tasks that encompasses many individuals and must meet many demands. The speed of this process and the cost of the products that it produces are very important in determining commercial success. In addition to modeling the cost

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[1] While there are several ways to design and manufacture a product, most methods contain the following steps in some form.

of the products that are developed, a method for determining the cost of the development process and the lead time required for various product family alternatives is also needed.

Two widely used metrics for product development performance are engineering effort and product development cycle time, also known as lead time. Engineering effort refers to the number of engineering hours (or person-quarters, person-years) that are needed to go from concept development to the end of pilot production. Lead time is the calendar time that passes from concept development to the end of pilot production. Increased engineering effort not only increases the wages of the engineers needed for a particular product, but also the opportunity cost of forgone projects given limited engineering resources. Increased lead time can reduce market share or revenue by delaying a product entry into the market [35, 66]. Competitive advantages can be gained in some fast-cycle industries if lead times are sufficiently reduced in certain product development stages [64]. The design and engineering effort required for variant designs can be significant. The development of four additional variants off of one base vehicle can add as much as 50% to the engineering effort required to design an automobile [67]. Analogous to the importance of production cost information detailed above, the ability to predict development cost and lead time can allow decision makers to make trade-offs between the speed or cost of a development effort and product features.

The first step in determining the engineering effort required to develop a new product is identifying which product and component characteristics are correlated. There are two levels of characteristics that influence engineering effort: project level and component level characteristics. Research related to the development of software shows clearly that reliable models account for both product and project related factors [68]. The product development project level includes the fabrication and assembly of all components needed to produce functionally equivalent products. There are also characteristics on the component level that are influenced only by the individual constituent components of the final product. Project level influences include the number of unique parts, the novelty of the development project, and the complexity of the component interfaces. Characteristics at the component level include component complexity and manufacturing process complexity, as well as tolerances and other part specific quality needs.

One of the earliest attempts to study engineering effort is Norden's analysis of the distribution of effort over a period of time for a development project. This research predicts that over the life of a development project effort will peak and then trail off until the project is completed [69]. The integral of Norden's effort distribution function would provide the engineering effort of a development project. Given the large portion of labor costs that make up design projects, engineering effort can provide a good estimate of design project cost [70]. Determining total engineering effort for a development process requires that the effort at each phase of the product development process be determined.

The first phases of the product development process are concept development, product planning, and advanced engineering. Adler, et al., estimate the engineering effort required for early phases of product development, such as identifying customer expectations and determining market position, as well as later stage activities such as field trials and testing. This research asks informants to estimate the 90th and 10th percentiles of their processing time for a given activity. This information is then used to model the product development process of a plastics manufacturer [71]. Roy, et al., study the relationship between detailed design time and component characteristics. Some of these characteristics include geometric quantities such as the number of holes, pockets, cutouts, etc. Other characteristics are general to the component, such as whether it is a structural part, surface part, the complexity, etc. Here complexity refers to the geometric complexity of the part. Simple prismatic shapes are the least complex, whereas a surface is the most complex. The effects of these variables on both quantitative, or direct design time, and qualitative, or "thinking" time, are analyzed [72]. However, since it is estimated that over half of work effort is spent performing tasks outside of the design process (.i.e. planning or cost estimation) [73], a multiplier would have to be applied to these design time estimations to determine the total cost. In addition to the engineering effort for the detailed design phase at the constituent component level, the engineering effort for the entire project must be approximated. During the detailed design phase of the development process, component specifications and design details must be communicated to other members of the development team to ensure that interfaces between components perform properly [74]. This contributes to engineering effort required for the development project as well.

The next phase of the product development process is where manufacturing and assembly processes are developed. First manufacturing processes must be developed for the individual component parts. Murmann illustrates that technical uncertainty increases the probability of development changes and thus increases engineering effort because of iteration [75]. On the project level, Smailagic, et al., relate the number of technologies (stamping, injection molding, etc.) required to manufacture a product to its complexity and find this complexity to be correlated with the engineering effort required. Bashir and Thomson determine a relationship between the severity of the requirements that a product must meet and development effort [70]. As with cost, the choice of manufacturing technology can have significant effects on engineering effort and is linked to product design. Clark, et al., demonstrate that product and process engineering efforts are positively correlated [67].

The final phase of the development process involves the prototyping and testing of the product. Franck and Rosen look at the effort required to develop both physical and virtual prototypes. The effort required is then broken down into that which is expended to build the prototype, and that which is expended to test the prototype. Effort required to build the prototype is based on the general complexity of the product being modeled, the ease of use of the prototype, and the amount of interaction the prototype allows. The amount of effort required to test the prototype is based on the ease and speed of the user to use the prototype and the ability of the user to interact with the prototype [76].

The time required for a product to go from concept to production can have dramatic effects on the success and profitability of the project. A 1987 calculation by Clark found that for an automobile development project, every day that a project is delayed costs $1 million [67]. Datar et al., note that decreased lead time in various phases of the development process increases market share in the computer component industry [64]. Boeing's ability to get their 767 to market eight months before the introduction of the Airbus A310 increased Boeing's sales [77]. Decreased development time allowed Sony to set the standard for compact disc players and permitted Atlas Door to charge a 20% premium compared to its competitors [65]. Some major companies have even adopted time-to-market as their principal metric of product development projects [78]. Similar to the estimation of engineering effort, the determination of product development cycle time depends on both component level and project level characteristics. These characteristics can affect the duration of the different phases of the development process in different ways.

In the early phases (concept development, product planning, and advanced engineering) of the development process an individual component's development cycle time will depend on the effort required to design that component and the resources available to complete this task. Adler, et al., use the number of people available to perform a given task as well as rules about work reallocation and probability of that task being needed to derive project lead time from engineering effort data [71]. The effort required must include the necessary iterations, as well as any time that is not spent on direct engineering. Smith and Eppinger show the amount of time required to complete a task can dramatically increase when iterations (based on rework ratios) are included [79]. At the project level, the aggregate amount of time that the early phases of the design process take is dependent on project characteristics. Clark and Fujimoto find that for the concept and planning phases of the automobile development process, lead time is dependent on product complexity (as determined by price), body variations, and product innovativeness [14]. The amount of task overlap can also affect development lead time; increasing the number of overlapped tasks increases the amount of iteration, and therefore increases the amount of effort required [80]. This increased effort can also increase development cycle time. A general rule is that almost every activity may start when the previous activity is eighty percent complete [75].

Similar to the effort required for detailed design phase of the development process, the cycle time required for the development of manufacturing and assembly processes will be related to the amount of effort required, the extent to which tasks are overlapped, and the resources available. After the fabrication and assembly processes are developed, tools and machinery must be purchased and/or designed and fabricated. Injection molding mold lead time can increase from one week for a simple part, to almost twenty-five weeks for very complex parts [35]. Current research indicates that product development process behavior is more dependent on process complexity than product complexity [81].

Since, the prototyping and testing phase of the development process require the fabrication of virtual and/or physical prototypes, the cycle time required for this phase of the development process will depend on the amount of effort required and the resources available. There may also be lead time required for any "soft tools", which are used to make the prototypes.

In addition to research that applies to the specific phases of the development process, further research has been carried out looking at the relationship between overall product development effort and lead time and project characteristics. Smith and Morrow provide an extensive review of this research [82], some highlights of which will be detailed here. Rockwell International used the complexity and engineering effort required for subsystems of previous projects to determine the engineering effort of a current project based on the complexity of its subsystems [83]. Griffin's work states that development lead time is dependent on the project's inherent complexity, the amount of change between the current product and the previous generation, and the number of functions providing input to the project [84]. Griffin proposes a complexity measure based on the number of product functions and finds that product complexity has a greater effect on cycle time than does newness. Griffin also observes that cross-functional teams and a formal development process reduce product development cycle time [85]. Bashir and Thomson promote the use of metrics as opposed to subjective estimates; this research points out that in addition to being inaccurate and biased, subjective estimations do not lend themselves to sensitivity analyses [68]. Bashir and Thomson also propose a method for determining product complexity that is based on functional decomposition and is more refined than Griffin's. In addition, Bashir and Thomson also recommended desirable criteria for metrics to be used when modeling the development process, these include that the metric be intuitive, sensitive, consistent, general, and simple [86].

Modeling of the product development process is a difficult task. It entails many complex tasks that are performed by various groups of people. The addition of human interaction makes modeling the product development process more difficult than the manufacturing and assembly processes [82]. A model of the product development process is proposed in Section 2.2. This model builds upon previous research and attempts to follow recommendations as well as work within agreed upon practices.

1.2 Problem Statement

Important trade-offs are made during the initial stages of product development (usually implicitly). These decisions are often made with incomplete information. Decisions about the sizes and shapes of individual parts drive the manufacturing processes that can be used to fabricate them. This initial "break-up" of parts also determines the amount of assembly that will be needed to produce a finished product. The more integrated and consolidated parts are, the less assembly will be needed, but this will also reduce the flexibility to share parts across variant products. These decisions also affect the costs of development, fabrication, and assembly.

The purpose of this research was to attempt to answer questions about the effects of these early product development decisions. Specifically:

- What are the cost savings from sharing parts and subassemblies across variant products for various manufacturing technologies and product architectures?
- What are the trade-offs between sharing of parts and parts consolidation?

This research developed and assembled cost estimation tools that explicitly presented the trade-offs for different manufacturing strategies using the limited information available during the early stages of the product development process.

1.3 Thesis Outline

Chapter 2 of this thesis outlines the methods that are used to make trade-offs between competing priorities in the rest of this thesis. Section 2.1outlines the process-based cost modeling methodology. Section 2.1.1 discusses the various types of cost models that can be used to determine the cost of a single product given varying specificity of product characteristics. A method for estimating the cost of assembly is described in Section 2.1.2. Section 2.1.3 proposes a method for determining part sharing as well as a method for assigning costs to product family members. Section 2.2 proposes a model for determining the engineering effort and lead time required for a product family. Section 2.2.1 explains how data were collected that facilitated the building of the model. Section 2.2.2 details the statistical analyses used to determine major factors that determine engineering effort for the various stages of the development process. Section 2.2.3

discusses how data were used to calculate engineering effort, cost, and development lead time.

Chapter 3 details the comparison of two alternative body-in-white architectures. Section 3.1 discusses the development, fabrication, and assembly costs for a traditional stamped steel unibody architecture. Section 3.2 looks at the costs of an alternative tubular steel architecture. In both cases the effects of sharing are shown on both the different cost categories and overall costs. Section 3.3 compares and contrasts the two architectures. Chapter 4 examines parts consolidation, as detailed by comparing a magnesium instrument panel beam with its steel counterpart. A base case is presented in Section 4.1, and alternative scenarios are examined in Section 4.2.

Chapter 5 includes insights gained from the development of the model and analysis of the case studies. Section 5.1 elucidates insights gained from the development of a process-based cost model for automotive product development. Section 5.2 discusses inferences derived from the analysis of the case studies. Section 5.5 details opportunities for extension of this work. Chapter 6 lists the conclusions drawn from this work. Supplemental data and figures referred to in the remainder of this thesis are found in the appendices of Chapter 7.

2. Methods

As mentioned, the purpose of this thesis is to examine the effects of early product development decisions. The estimation methods used in the subsequent analyses of this work are detailed in this chapter. Section 2.1 covers the process-based cost modeling techniques used to estimate fabrication and assembly costs. Section 2.1.1 discusses the modeling of fabrication costs for single products. Section 2.1.2 describes the process-based cost model used for estimating assembly cost. Section 2.1.3 discusses the calculation of part sharing metrics and the cost savings from part sharing. Section 2.2 details the development of a process-based cost model for the automotive product development process. The method of data collection and the statistical analyses of this data are discussed in Sections 2.2.1 and 2.2.2 respectively. Finally the details of the development cost model are discussed in Section 2.2.3.

2.1 Process-based Cost Modeling

Process-based cost modeling (PBCM) is an early stage generative cost estimation tool which uses various part and process characteristics to determine manufacturing or assembly costs. Process-based cost models for several manufacturing processes exist and have been used to answer numerous research questions [27, 36, 87-89]. Process-based cost models are constructed by working backward from cost -the model's objective- to physical parameters that can be controlled – the model's inputs. The modeling of cost involves correlating the effects of these physical parameters on the cost-determinant attributes of a process and then relating these attributes to a specific cost [59]. The relationship between physical parameters and cost-determinant attributes is determined either by using physical relationships or through statistical analysis.

2.1.1 Modeling Single Product Fabrication

As mentioned above, process-based cost modeling is the mapping of product and process characteristics onto categories of cost (i.e. materials, tooling, etc.). The inputs required for a PBCM can be broken into four main categories: part and material related, process related, operational, and financial. Table 2-1 shows representative examples of each type of input. For a metal stamping, part data would be used to determine the required press tonnage and a line rate. These cost-determinant attributes are combined with process, operational, and financial inputs to determine both fixed and variable costs. Process-based cost modeling is summarized in Figure 2-1.

Table 2-1. Inputs for Process-based Cost Models

Part and Material	Length Mass Complexity
Process	Reject Rate Down Time Power Requirement
Operational	Production Volume Days Worked Per Year Hours Worked Per Day
Financial	Rate of Return Wage

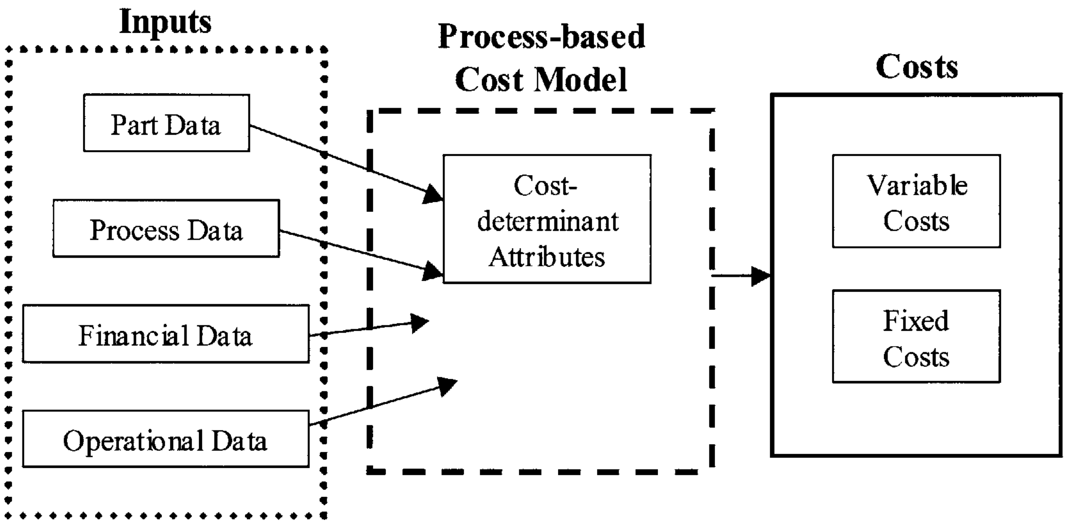

Figure 2-1. Schematic of Process-based Cost Modeling

Variable costs are those costs that scale linearly with production volume. Examples of variable costs are shown in Table 2-2. The material cost category includes the primary or raw material required for a part as well as any process consumables, such as lubricants or cleaners. The type of material, the amount of scrap, and the value of scrap are all important factors in determining material cost. Labor cost includes only the direct (indirect labor is captured in the overhead cost category) labor required for part fabrication. The fully burdened (including benefits) wage, amount of planned and unplanned downtime, and number of laborers needed are some of the factors that affect labor costs. Energy costs include the cost of running machinery as well as any additional heating or other energy related input. Cycle time, heating requirements and energy cost are important factors in determining energy costs. Variable costs can make up a considerable portion of total cost for some manufacturing processes. The definition of variable or fixed cost is highly dependent on the situation and the time horizon being considered [90]. In some cases unionized labor or contracted materials shipments would be considered fixed costs.

Fixed costs include those items that do not scale with production volume.[2,3] Examples of fixed costs are also shown in Table 2-2. Main machine cost includes the cost of the primary machinery used for the fabrication of a part as well as the installation cost of the machinery; installation cost is usually proportional to the machine cost. This cost is usually determined by amortizing the total machine investment over the estimated lifetime of the machine. In the case of dedicated manufacturing, the cost is then the cost of one year of machine use. For non-dedicated manufacturing, the cost is the percentage of yearly machine capacity used times the cost of one year of machine use. Whether or not a machine is dedicated, cycle time, part size, and manufacturing technology all contribute to the main machine cost. Tooling cost includes the cost of dedicated tools required for the manufacturing process. Tooling cost is usually amortized over the life of the product, the tooling cost is then for one year of tool use. Product size, complexity, tool material, and any required tool action (such as release springs or pins) can affect tooling cost. Overhead costs include managerial labor as well as other support services. Overhead costs are usually proportional to yearly machine, tooling and building costs. Building cost is the cost of the space that the manufacturing operations occupy. Building cost is amortized over the life of a building; building cost is then the cost for one year of building use. Auxiliary equipment costs are the costs of equipment that is not directly used in the fabrication of the product, but is needed for the manufacturing operation. These costs would include things like conveyance systems and lockout equipment.

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[2] Fixed cost are actually only fixed for a certain range of production volumes. For example, if production exceeds a certain limit, two tools or machines may have to be purchased.

[3] Certain equipment and facilities may be non-dedicated. This allows machine and facility cost to scale with production volume and assumes that some other product will use the remaining machine and facility capacity.

Auxiliary costs are usually proportional to main machine cost. Finally, maintenance cost is the cost of upkeep on machines, tools, and auxiliary equipment. Maintenance cost usually scales with the yearly cost of machines, tools, and equipment. In addition to the yearly fixed costs, process-based cost modeling can also be used to determine required investments. The required investment typically includes machine, tooling, building, and auxiliary equipment cost. In the cases of machine and building costs, the investment would include the costs of the machine and building over the life of the product. The estimation of investment would allow decision makers to compare the value at risk for alternative products and manufacturing technologies.

Table 2-2. Fixed and Variable Cost Examples

Variable Costs	Fixed Costs
Materials	Main Machine
Labor	Tooling
Energy	Building
	Overhead[4]
	Auxiliary Equipment
	Maintenance

The value of process-based cost modeling arises from its ability to detail the major driving factors of costs, as well as its ability to categorize these costs. This categorization is rare in predictive costing tools, and allows decision makers an opportunity to look at possible trade-offs that might merit more in-depth analysis. A representative example of the output of a process-based cost model is shown in Figure 2-2, where costs are broken down into several categories. For robust physically-based models, this exploration of underlying cost drivers can be pursued to fine levels of detail regarding product design or processing conditions. When process-based cost models are used in a spreadsheet format, the specificity of the variable inputs and the transparency of the calculations facilitate straightforward multivariable sensitivity analysis. Shown in Figure 2-3 are the effects of production volume and labor cost on part cost for a generic injection molded part. Process-based cost modeling can also be used to determine which manufacturing technology is preferred for a given set of conditions. Figure 2-4 shows the comparison

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[4] While overhead can be both fixed (relating to machines, building, etc.) as well as variable (relating to materials handling, labor supervision, etc.) it is included as a fixed cost.

between an injection molded and stamped part of similar size and complexity. Process-based cost modeling can allow decision makers to analyze competing engineering solutions over a wide range of operational alternatives.

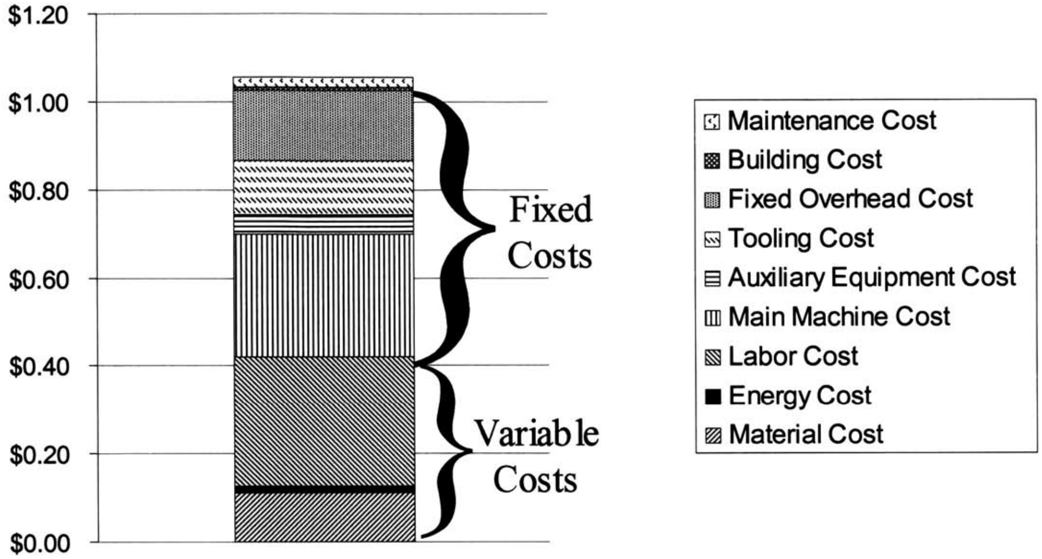

Figure 2-2. TCM Cost Breakdown of Injection Molded Part

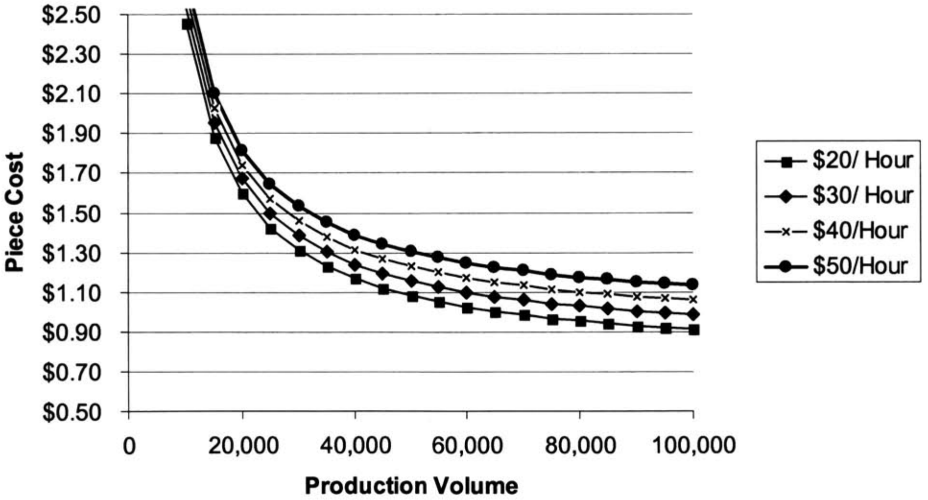

Figure 2-3. Effects of Production Volume and Hourly Wage on Piece Cost

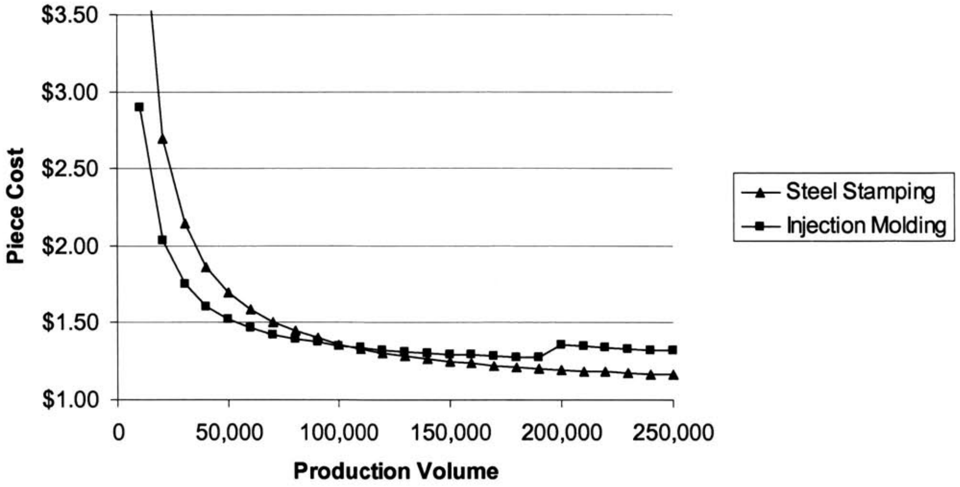

Figure 2-4. . Piece Cost at Various Production Volumes for Stamping and Injection Molding

Determining the fabrication cost of a component part is useful at many stages of the development process and can be required for several different reasons. During the early stages of the development process when limited information is available, cost estimates may be used to select between alternative architectures or manufacturing technologies. At later stages of the development process when more information is available, cost estimates might be used for competitive bid or pricing decisions. At other times detailed cost information about an existing process can be used to do an in depth analysis. PBCMs can be used to determine the effects of process changes or to establish the focus of improvement efforts. Process-based cost modeling is an adaptable tool that can be used in all these situations.

Traditional process-based cost models required information about several aspects of the part. This could include details such as minimum and maximum wall thickness, as well as other specific part information. While these "full" models are useful when such information is known, they are not as useful in the earliest stages of development when only limited information is available. In response to this problem scaled down cost models were developed. These limited information models use a smaller number of inputs to estimate the other inputs that were explicitly assigned in the "full" models. In addition to being of use during the very early stages of the development process, these limited information models can also be used when dealing with a large number of parts, for which the use of the “full” models would be exceedingly laborious. When an in-place process is being analyzed, the predictive capabilities of process-based cost models are of little use. They can however serve as a financial calculator. These “financial” models can take intermediate inputs such as cycle time, machine cost, or tool cost and calculate part cost. They can also give a detailed cost breakdown, be used to determine the major cost drivers for a given manufacturing system, or determine the sensitivity of the system to changes such as labor cost. Process-based cost modeling fulfills the requirements put forth by Noble and Tanchoco. It analyzes and presents quantifiable information, allows the decision maker to process and integrate uncertain or incomplete information throughout the design process, and allows the designer to determine the trade-offs of decisions [43].

2.1.2 Assembly Cost Modeling

To determine the total fabrication cost for a product with multiple parts the cost of assembly must be calculated. A given assembly can consist of several parts and several subassemblies. As mentioned above, Boothroyd, et al., propose a method for determining the labor portion of assembly cost based on data obtained from observing the time various subjects required to complete certain tasks [28]. While this would be adequate to determine the cost for assembly processes that are largely manual, it does not reflect the cost of automated assembly operations that require considerable amounts of equipment and fixtures. In response to this need, a process-based cost model of assembly that takes into account the costs of equipment, tooling (fixtures), and labor has been developed.

Process-based cost modeling of assembly uses relational (database-like) tables containing information about the assemblies, the joining methods required by these assemblies, and process-specific information about joining methods to estimate an assembly cost. A schematic of the process-based cost modeling of assembly is shown in Figure 2-5. The methods table of the model contains data about each of the methods that could be used in an assembly process. This data includes characteristics of the joining method that are used in determining both the cost-determinant outputs and the final cost for the joining method. Quantities such as the speed at which a method can join, the time it takes for a method to begin and finish its process, and whether or not the method is a form of continuous joining are included in the methods table. Also included in the methods table are the equipment and fixture costs, floor space required, the maximum number of equipment pieces that can be located at a given station, and the requirements for labor and energy. The subassembly table contains the name and a unique identification number for each subassembly as well as the number of parts in that subassembly. In the assembly detail table the type and amount (quantity or length) of the joining methods required for each subassembly are specified. As with process-based cost models for part fabrication, inputs for financial and operational information are also provided within the assembly model.

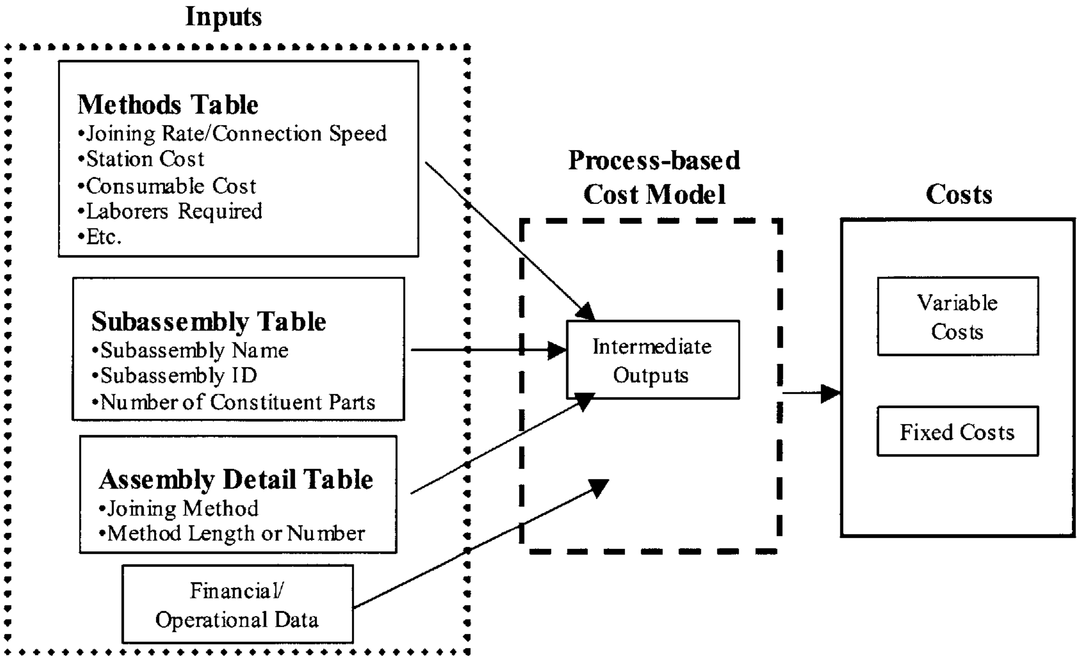

Figure 2-5. Schematic of Technical Cost Modeling for Assembly

The calculation of intermediate outputs for assembly is markedly different than that of fabrication processes. In fabrication processes cycle time is determined by process characteristics and the number of machines required is then determined. For the assembly process, the required production volume and the available amount of production time (uptime, working days per year, etc.) determine the cycle time. The number of machines, and thus stations, required for each joining process is determined by the amount of joining required for a given subassembly and the speed of the joining process. This also is used to determine the number of fixtures required. Whereas additional capacity is added in parallel for fabrication processes, additional capacity is added in sequence for the assembly process. This is due to the importance of uniform output in assembly (each subassembly goes through all the same stations). The cost of individual fixtures, machines, and base stations are then used to determine tooling and equipment cost for that joining method for that subassembly. Building costs is determined from the number and type of stations, the building space required by the stations, and the cost of the building space. Unlike cost models for fabrication, the costs of all equipment and building space are charged to the product regardless of any unused capacity. The costs of maintenance and overhead are calculated in the same way as that of fabrication modeling. The cost of labor is dependent on the amount of equipment, while the number or amount of joining determines the cost of consumables and energy. Once the cost of a joining method for a given subassembly is determined, it is then summed with the costs of the other joining methods for that subassembly to determine the total cost the assembly. As with process-based cost modeling for fabrication the costs for assembly are broken down into cost categories. Since an assembly can consist of parts and subassemblies, the cost of an assembly must take into account not only the cost of assembling the parts for that assembly, but the costs of assembling the constituent subassemblies of that assembly as well. This is important for determining the cost savings or penalty that exists for parts consolidation efforts. A representative example of an assembly cost breakdown is shown in Figure 2-6. Assembly cost models used in concert with fabrication cost models allow for the accurate estimation of product manufacturing costs.

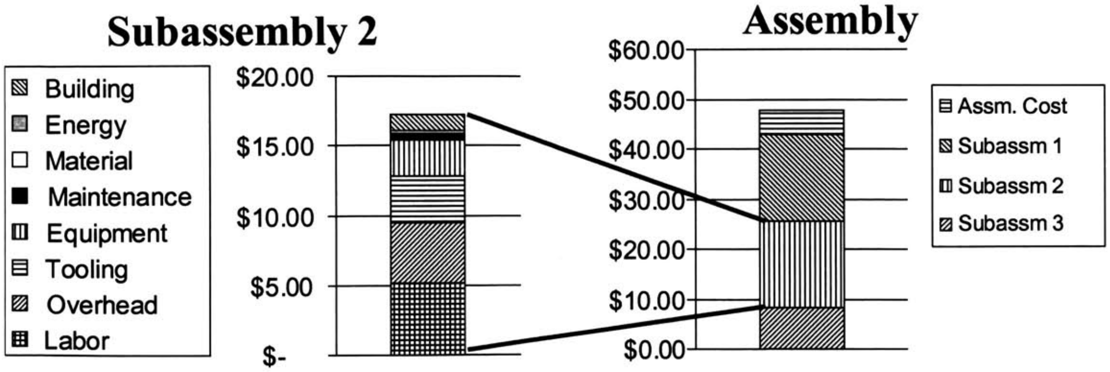

Figure 2-6. Cost of Subassembly and Aggregated Assembly Costs

2.1.3 Calculating the Cost of Shared Parts

As mentioned in Section 1.1.1, in order to diagnose the impact or value of various part sharing strategies, it is first necessary to devise a metric that characterizes the amount of sharing within those strategies. To this end, several ordinal measures of part and assembly commonality were used in this thesis. As noted by Wacker and Treleven, such measures allow for relative comparison of product family alternatives [22]. This basic commonality metric (*C*), used in this work, is defined as the ratio between the number of parts shared and the number of parts that could be shared. This ratio is calculated for each line item in the combined bills of materials for all variant products in the family being analyzed. These quantities are summed and then divided by the total number of line items. Specifically, the amount of sharing is calculated as follows:

$$C = \frac{\sum_{i=1}^{d} \left(\frac{\sum_{j=1}^{m} \gamma_{ij} - 1}{m-1} \right)}{d}. \tag{2-1}$$

Where $\gamma = 1$ if variant *j* contains part i, and zero if it does not. Here *m* is the total number of product variants and *d* is the number of distinct items in the bill of materials. An example bill of materials for a product family is shown in Table 2-3. The sharing calculation for this product family is shown in Table 2-4. In this example *C* is equal to 0.375. This same methodology can be used to determine the commonality of subassemblies in a product family by replacing the part line items with subassembly line items. The part commonality measure would usually be used in concert with part fabrication costs, while the assembly metric would be used with assembly costs.

Table 2-3. Example Bill of Materials for Product Family

		Variants		
		V1	V2	V3
Parts	A	X	X	X
	B		X	
	C	X	X	
	D			X

Table 2-4. Example Part Sharing Calculations

		Parts Shared	Possible Parts Shared	Percent Shared
Parts	A	2	2	100%
	B	0	0	0%
	C	1	2	50%
	D	0	0	0%

For a commonality metric to be relevant and useful, it should reflect the relative production volumes as well as some measure of cost and/or complexity of the parts being analyzed [21, 22]. Generically, the following is a sharing metric that includes such a measure:

$$C_C = \frac{\sum_{i=1}^{d} \left(\phi_i \frac{\sum_{j=1}^{m} \gamma_{ij} - 1}{m-1} \right)}{\sum_{i=1}^{d} \phi_i} \tag{2-2}$$

where ϕ_i is the measure of a part's relative importance, such as it's complexity, mass, or cost. All other items are as previously defined. Incorporating the effect of differing production volumes for the variant products of the family, leads to a relationship of the form:

$$C_{P,C} = \frac{\sum_{i=1}^{d} \left(\phi_i \frac{\sum_{j=1}^{m} \left(P_{ij} \gamma_{ij} \right) - \min\left(P_{ij} \right)}{\sum_{j=1}^{m} P_{ij} - \min\left(P_{ij} \right)} \right)}{\sum_{i=1}^{d} \phi_i} \qquad (2\text{-}3)$$

here P is the production volume for variant j and $\min\left(P_{ij}\right)$ is the minimum variant production volume. Table 2-5 shows production volumes for variants containing parts of different masses. A breakdown for the calculation of $C_{P,C}$ is shown in Table 2-6. For this example $C_{P,C}$ is equal to 0.55.

Table 2-5. Example Bill of Materials for Product Family with Varying Production Volumes

			Variants		
		Mass	V1	V2	V3
Parts	A	5	100	50	30
	B	3		50	
	C	2	100	50	
	D	7		50	30

Table 2-6. A Breakdown for the Calculation of Sharing

		ϕ_i	$\sum_{j=1}^{m}\left(P_{ij}\gamma_{ij}\right) - \min P_{ij}$	$\sum_{j=1}^{m} P_{ij} - \min(P_{ij})$	$\left(\phi_i \frac{\sum_{j=1}^{m}\left(P_{ij}\gamma_{ij}\right) - \min(P_{ij})}{\sum_{j=1}^{m} P_{ij} - \min(P_{ij})}\right)$
Parts	A	5	150	150	5.0
	B	3	20	150	0.4
	C	2	120	150	1.6
	D	7	50	150	2.3

Finally, before computing any of the above measures of platform commonality, it is necessary to establish a more formal definition for the value of γ, the variable describing a part's shared status. This is required because in real-world products shared subassemblies and components do not have to be identical. Some components may share the majority of forming production steps, differing only because of limited finishing operations such as trimming or drilling of holes. For the purpose of this work a part or assembly was considered shared if it used the same primary forming tooling and equipment as another part in the family.

As highlighted in Section 1.1.3 the ability to assign costs to the products and activities that are responsible for them is of great importance. There are two types of cost that can be calculated for shared parts: incremental cost and shared cost. The incremental cost of a constituent part or variant is the extra cost that is incurred to produce that part or variant assuming that the tooling and equipment cost for the original parts has already been paid. The shared cost of a constituent part or variant is the production volume weighted ratio of that variant's cost contribution to the total cost for a part or subassembly. For the example shown in Table 2-5 the shared cost for variant three would be one sixth the total cost to produce part A for all three variants. For the product family the manufacturing and assembly cost of all variants can be determined as if each variant were produced independently, without the benefits of sharing. These costs can then be summed to determine the cost of the entire product family assuming no sharing. The cost assuming no sharing is then compared to the manufacturing and assembly costs of the product family if certain subassemblies and components are shared between variants. Comparing these values leads to the following method of determining the cost savings (S) due to parts sharing:

$$S = \frac{\sum_{i=1}^{d}\sum_{j=1}^{m} \mathrm{X}_{ij} - \sum_{i=1}^{d}\sum_{j=1}^{m} \Delta_{ij}}{\sum_{i=1}^{d}\sum_{j=1}^{m} \mathrm{X}_{ij}} \tag{2-4}$$

where X_{ij} is the cost of a given part for a variant assuming that there is no sharing and Δ_{ij} is the shared cost of a part for that variant. The shared and incremental investments for parts and variants can also be determined. The methods described in Section 2.1 are used to estimate manufacturing and assembly costs for this work.

2.2 Development Model

To capture the total cost of a development project and ensure appropriate trade-offs among competing options, the development cost and lead time of the project should be examined in addition to fabrication and assembly costs. Roy, et al., propose that when modeling the cost of the development process, that process should be well understood, dissimilar products should not be mixed, and data for as many designs as possible should be collected [72]. The development process should also be well established and stable. This section details the methodology used to model engineering effort and lead time for the development of automotive body structures and closures. Data about similar parts and subassemblies was collected at various stages of the development process. A model was then formulated to relate this data to engineering effort and lead time. A diagram of the stages in the automotive product development process examined is shown in Figure 2-7.

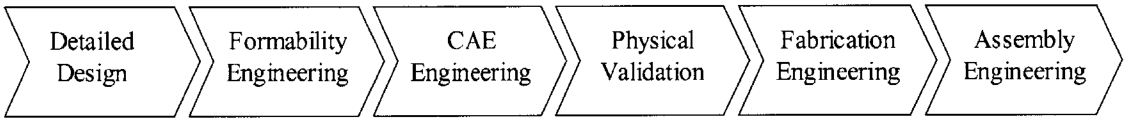

Figure 2-7. Stages of Automotive Product Development Process

2.2.1 Data Collection

As mentioned above, the product development process includes the steps from concept development to pilot production. For the purpose of this work the concept development and product planning stages of the development process were assumed completed. The pilot production and ramp-up phase of the development effort also were not be modeled. A model of the advanced engineering, prototyping, and processes development phases of the product development process is proposed. The advanced engineering phase of the development process for automotive structures and closures includes the detailed design of individual parts as well as the determination of the formability of these parts. Next both virtual and physical prototypes are produced for computer aided and physical validation. It should be noted that the computer aided and physical validation phases of the development process described and modeled in this work include structural validation only and do not address the process of determining vehicle crash worthiness. The process development phase includes the fabrication engineering required for the individual parts and the engineering required for the assemblies and subassemblies of the vehicle or closure. Engineering group managers responsible for the various stages under consideration in both truck and car groups were contacted and asked to supply the names of engineers that could be surveyed. Engineers were then contacted and asked to schedule an appointment to be surveyed face-to-face for approximately one half hour.

The detailed design stage of the development process consists of designing an individual part that meets the specified structural and packaging requirements. These requirements are subject to change. The designing engineer (designer) is responsible for the part until it is released for fabrication. To determine the cost drivers of the detailed engineering stage of the development process the survey shown in Appendix Section 7.1.1 (on page 111) was administered to designing engineers. Each engineer was asked to select three recently completed (released) parts of varying size and complexity. In addition to contact information the engineers were asked to specify how long they had been designing engineers. It was conjectured that more experienced designers would be more efficient and design comparable parts in less time than those designers with less experience, and that this would have to be accounted for to increase the fidelity of the model. The name and manufacturing technology used to fabricate the part were also noted. The designer was asked to estimate the geometric complexity of the part based on a five-point scale. The designer was told that a part such as a simple bracket was a "one", while a complex part such as a floor pan was a "five". The length, width, and height of a box in which the part would fit were also collected. The designer was then asked if the part contributed to the structural integrity of the vehicle required for crash worthiness. Geometric complexity, part size, and structural nature of the part are similar to data collected by Roy, et al. [72]. Similar to Roy, et al., increasing complexity, size, and a part being structural were hypothesized to be positively correlated with engineering effort. Next the designer was asked to estimate the total time spent working on this part at the computer. It was specified that the estimate should include all iterations and any work done between the reception of packaging requirements until the part was released for fabrication. The calendar time or number of days required to complete this amount of work was queried and the designer was asked to estimate the amount of time that would be required to make a length or width change to the part while maintaining all relevant features and relational spacing (not a simple stretch). The designer was also asked how long it would take to add a representative feature (hole, pocket, etc.) to the part. It was specified that these time estimates should include any additional iterations that would be expected or any changes to other features affected by the feature addition. The estimates were recorded as a percentage of the original design time. Next the designer was asked how many major design iterations were performed on the part and to estimate the amount of overlap for the design project (subassembly of parts that the part in question interacted with) that included their part. The purpose of this question was estimate how much information the designer had about other parts that the part that was being designed interacted with prior to beginning their design activities. A "one" was specified as very little information (all tasks were being done in parallel), while a "five" was specified as almost complete information (tasks were sequential and other parts were mostly complete). It was hypothesized that a more parallel process would lead to more iterations and thus more effort. The engineer was then asked to estimate the likelihood of having to change the part once it was prepared for release to fabrication (a feasible engineering solution had been found). The sensitivity of the part in question to changes in other parts that it interacted with was also asked. These questions consisted of a three-point scale going from "one" (representing not likely/not sensitive) to "three" (representing very likely/very sensitive). Finally the engineer was asked to estimate the probability of having to change the part after a feasible engineering solution had been derived. This final set of three questions was asked to better assess the probability of iterations and sensitivity of the part to iterations in other parts. It is similar to work done by Yassine, et al. used to determine rework probabilities [91]. Twenty-three designing engineers were surveyed producing fifty-nine responses.

Engineers responsible for determining the formability of parts were also surveyed. These engineers are responsible for determining if a design can be manufactured to at an acceptable level of quality. They analyze stresses that arise from the manufacturing process and determine if part defects will occur. There is a significant amount of overlap between this stage of the development process and the detailed design stage. Due to the overwhelming amount of stamping used in automotive manufacturing, stamping is the only process considered in this survey. Formability analyses for other processes are contained in the estimation of the engineering effort required for that process. Each engineer surveyed was asked to select four parts of varying size and complexity for which formability analyses were recently completed. The survey administered to these formability engineers is shown in Appendix Section 7.1.2 (on page 113). Similar to the designing engineer survey, information about the engineer's experience was tabulated. Information about the part's complexity and size were also collected. The complexity estimated is again based on a one to five scale where a "one" represents a very simple part, while a "five" is a very complex part. Again increasing size and complexity were hypothesized to be positively correlated with the amount of effort required for the formability analysis. Whether or not the part was a surface (seen by the consumer on the surface of the vehicle) part was also queried. Surface parts have higher quality standards than those that are not seen by the customer and thus were hypothesized to require more formability engineering effort. The engineers were then asked to estimate the engineering effort required for one formability analysis of the part. The number of iterations was also noted. Unlike design engineering, the number of major iterations is tabulated in a computer system used to access data about the part, this data was gathered from the system. The calendar time required for the entire set of iterations was also recorded. Since formability analyses are run on large computers with extensive processing power, it was conjectured that these computers could contribute significant cost to the formability analyses. The amount of computer processing time for each iteration was also documented. Six engineers were surveyed yielding data about twenty-four parts.

Engineers from the computer aided engineering (CAE) groups were also surveyed. These engineers are responsible for assessing the modal response, structural rigidity, and durability of the body-in-white (BIW) or closure using computer models. They receive completed detailed designs of individual parts and assemble them into either the BIW or closure to be tested. There is a moderate amount of overlap between the detailed design, formability, and CAE stages of the development process. Engineers in this group go through a standardized set of tasks to determine if the closure or BIW meet predetermined specifications. Engineers in these groups were asked to select recent projects that they had completed. They were then asked about entire projects as well as individual tests or procedures. The survey administered to CAE engineers can be seen in Appendix Section 7.1.3 (on page 114). First these engineers were asked to describe the type of project they had worked on. They were then asked about the major manufacturing technology and material of the assembly. Given the consolidated nature of these analyses, there was little variability in these responses (i.e. steel stamped door or steel stamped body-in-white). The engineers were then asked to estimate the amount of effort required to set up the analysis. This time included the effort required to mesh the models received from design engineering for finite element analyses as well as to apply loads and design testing procedures. Next the engineers were asked to estimate the effort required to run the analysis. This effort included the time required to analyze the results and create any required documentation or figures. Finally these engineers were asked to estimate the calendar time required for the entire process. Unlike the previous two stages of the development process there are few individual characteristics that could be used to estimate the amount of effort required. This was due to the aggregated nature of the systems under consideration as well as the standardization of the analyses. Fifteen CAE engineers were surveyed yielding information about eight bodies and eleven closures.

Engineers responsible for the physical validation of both the BIW and closures were also surveyed to determine the amount of engineering effort required for the testing of physical prototypes. These engineers run tests on physical prototypes similar to those performed by the CAE group and validate that the results agree with those generated by the computer models. The survey administered to the validation engineers can be seen in Appendix Section 7.1.4 (on page 115). Similar to the CAE group, these engineers were asked about entire projects as well as individual tests. They were asked to estimate the amount of effort required to perform the validation for the project or individual test. They were also asked about: (1) the total number of engineers and technicians that worked on the project; (2) the calendar time required to complete the project or test; (3) under what circumstances a given test could be used for other variant products in the product family. Seven validation engineers were surveyed yielding information about four bodies and seven closures. In addition to information about the engineering effort required to test the physical prototypes, information about the cost of soft tooling, materials, and labor to assemble the prototypes was tabulated.

Information about the engineering required for the fabrication of individual parts was also collected. Unlike the previous stages of the development process, one engineer or a small group does not perform this set of tasks. This set of tasks includes the development of how the process will work, the selection of the machinery required to fabricate the part, and the design of any tooling. Detailed data that included individual part characteristics was only available for stamped parts. This data was collected from engineering managers who were responsible for overseeing the different portions of the process development stage. The first portion is the effort related to the machine section and process design; these are described as expensed tasks. The other portion of the process development stage is the actual design of the dies; these are described as capital tasks. The survey shown in Appendix Section 7.1.5 (on page 116) was administered to determine the cost drivers of the process development stage. Data about the size and complexity of the parts was tabulated. It was hypothesized that increasing part size and complexity would lead to more effort in both the expensed and capital portions of the process development stage. Data about whether or not a part was a surface part, thus requiring a higher quality standard, and the number of dies required to form the part was also noted for capital tasks. Data about the expensed portion of the process development stage was collected from two managers and data about the capital portion was collected from one manager for thirteen stamped parts. In addition to the detailed information gathered for stamped parts, data about other processes was also tabulated. In these cases process experts were asked to estimate the total amount of engineering effort including formability, machine selection, process design, and tooling design for parts of varying complexity and size. These experts were interviewed for data about die-casting, tube hydroforming, roll forming, and both tube and stretch bending.

Like fabrication engineering for individual parts, assembly engineering is a complex set of tasks that requires several people. Data about the engineering effort required for the assembly process was collected from assembly engineering experts who keep track of the engineering effort required for certain subassemblies. The survey shown in Appendix Section 7.1.6 (on page 117) was used to collect data about the assembly engineering process. Engineers were asked to estimate the overall complexity of the assembly on a scale of one to five. They were told a simple bracket assembly was a "one" and a complex motor compartment or bodyside was a "five". Next the amount of joining required for the assembly was queried. Joining methods were converted into the equivalent number of spot welds so that a consistent metric could be used. The number of distinct joining methods and number of parts in the assembly were also recorded. It was hypothesized that increasing complexity, number of joining methods, number of parts, and amount of joining would all be positively correlated with engineering effort. These engineering experts were asked to estimate the total amount of engineering effort required to design the assembly process, design any tooling, and determine equipment needs. They were also asked to estimate the amount of calendar time required to complete this assembly engineering. Finally they were asked to estimate the percentage of the original effort that would be required to assemble a slight variant of the original subassembly. Three engineers provided data for seventeen subassemblies.

2.2.2 Data Analysis

Similar to process-based cost models for production and assembly, product and assembly characteristics were used to determine intermediate outputs that could then be used to predict engineering effort and development lead time. Linear regression analysis was used with the data collected from the surveys to determine which part and assembly characteristics led to increased engineering effort. Due to the highly proprietary nature of this data, all engineering effort and calendar time quantities were normalized by the mean of the data set.

Data for the detailed design stage was analyzed to determine which part and project characteristics determine engineering effort and lead time. After incomplete survey results and duplicate parts were removed, forty-nine responses remained. Very large and very small parts were removed from the data set so that outliers did not overly influence results; i.e., parts with a size to average size ratio of smaller than 0.001 or larger than 4. The remaining data set contained thirty-eight parts. Table 2-7 shows the Pearson correlation matrix for the survey data, statistically significant ($p \leq 0.1$)[5] correlations are marked; possible explanations of statistically significant correlations are as follows. As hypothesized both part size and part complexity were positively correlated with computer design time. Whether or not a part was structural (denoted with a one if true) was also positively correlated with computer design time. The amount of project overlap was negatively correlated with the amount of computer design time. This could have been due to the increased iterations, and thus design effort that arose from incomplete information. It could also have been due to the fact that very large parts that required considerable engineering effort would have been initiated before other part information was available. Sensitivity to other part changes was positively correlated with the designer's experience. This was not unexpected, assuming that as a designer gained more experience they would be responsible for parts that require expeditious changes in an uncertain environment. The number of iterations was negatively correlated with the size of the part and the amount of project overlap. A high amount of project overlap (a "one" on the survey) corresponded to tasks being done in parallel and little information about other parts in the project being known at the commencement of design activities for the part in question. It was reasonable to assume that this would lead to more iterations than if a more sequential (a "five" on the survey) project plan had been used. It was not evident why smaller parts would require more iterations, except that they were easier to change than larger parts. This, however, did not show up in the size likelihood of change relationship. Whether or not a part was structural was negatively correlated with both the amount of project overlap and the likelihood of change. The negative correlations for structural parts with the amount of project overlap and the likelihood of change was intuitive. Given the importance of structural parts it is not unexpected to believe that they would have been designed first (when little information about other parts was known) and that change would have been unlikely after a feasible solution had been found. Part complexity was positively correlated with part size as well. While there is no intrinsic reason for large parts to have been more complex, it was reasonable that the two quantities were positively correlated. As expected, both sensitivity to an interacting part's change and the likelihood of a part's changing were positively correlated with the

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[5] p is the probability of the null hypothesis being true, given the value of the test statistic.

probability of a part changing. However this probability was not statistically significantly correlated with the number of iterations or the amount of project overlap. Most results from the analysis of the survey proved to be both intuitive and reasonable.

To determine the major part and project characteristics that affect computer design time, several linear correlation models were tested. As mentioned earlier, a desirable characteristic of a cost estimation or modeling tool is that it be able to use data available at the early stages of the design process. Information such as the probability of change and the number of iterations did not meet this standard and were not included in the models tested. Table 2-8 shows seven different linear regression models that were used to estimate computer design time based on part and project characteristics. Models one and three included the structural part variable. In neither case was this coefficient statistically significant; in both cases it was negatively correlated with design effort, this did not seem reasonable. In both models that contained designer experience, the coefficient was not statistically significant. The model that contained part complexity, part size, and project overlap performed only marginally better (based on R^2)[6] than the model containing only part size and project overlap. There was a statistically significant positive correlation between part size and part complexity, as seen in Table 2-7. Since model six contained only one of these variables and performed almost as well as other models, it was used to determine computer design time in the subsequent sections of this work. The data predicted using model 6 and collected data from the surveys are plotted in Figure 7-1 located in Appendix Section 7.2. A plot of standardized residuals verses predicted values for model 6 is also shown in Figure 7-2. This figure shows the error terms were evenly distributed and independent of the predicted value.

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[6] R^2 is the multiple regression correlation coefficient, and measures the proportion of variability in the data set that is explained by the regression.

Table 2-7. Pearson Correlation Matrix for Designer Survey Results

	Computer Design Time	Years Experience	Number of Iterations	Structural	Size (dm^3)	Part Complexity	Amount of Project Overlap	Likelihood of Part Change	Sensitivity to Part Change	Probability of Change
Computer Design Time		-0.083	-0.173	0.213*	0.673**	0.463**	-0.221*	0.012	-0.036	-0.046
Years Experience			-0.047	0.016	0.009	0.156	-0.080	-0.009	0.416**	-0.063
Number of Iterations				0.067	-0.240*	0.004	-0.260*	0.031	0.049	-0.048
Structural					0.150	0.196	-0.476**	-0.227*	-0.054	-0.164
Size (dm^3)						0.503**	-0.015	0.194	0.086	0.163
Part Complexity							0.039	0.170	0.289**	0.071
Amount of Project Overlap								0.069	0.031	0.142
Likelihood of Part Change									0.139	0.871**
Sensitivity to Part Change										0.252*
Probability of Change										

*p<0.1
**p<0.05

Table 2-8. Linear Regression Models of Detail Design Survey Data[1]

Model	Constant	Years Experience	Structural	Size (dm^3)	Part Complexity	Amount of Project Overlap	R^2	F-Stat
1	0.175 (0.095)	-0.005 (0.004)	-0.013 (0.065)	0.002 (0.000)	0.044 (0.029)	-0.036 (0.021)	0.47	7.52
2	0.166 (0.081)	-0.004 (0.004)	-- --	0.002 (0.000)	0.042 (0.028)	-0.034 (0.018)	0.48	9.67
3	0.153 (0.094)	-- --	-0.009 (0.065)	0.002 (0.000)	0.037 (0.029)	-0.034 (0.020)	0.46	8.99
4	0.147 (0.080)	-- --	-- --	0.002 (0.000)	0.037 (0.028)	-0.032 (0.018)	0.48	12.3
5	0.084 (0.075)	-- --	-- --	0.002 (0.000)	0.034 (0.029)	-- --	0.44	15.7
6	0.230 (0.050)	-- --	-- --	0.002 (0.000)	-- --	-0.031 (0.018)	0.47	17.3
7	0.082 (0.095)	-- --	-- --	-- --	0.096 (0.029)	-0.035 (0.021)	0.23	6.5

[1] Standard Errors in Parentheses

To determine computer design time required to make changes to existing detailed designs, data about the effort required to make these changes was collected. Data was gathered about the engineering effort required to make scale changes and to add features to the parts analyzed above. This data was normalized by the mean of the computer design time required to make a scale change for the part. Parts that required either more than or less than ten times the mean design time to make scale changes were removed from the data set. The remaining data set contained twenty-four parts. The correlations between part characteristics and engineering effort required for scale changes are shown in Table 2-9. There are statistically significant ($p \leq 0.05$) positive correlations between the amount of time required for scale changes with size, part complexity, and the original amount of computer time required to design the part. It was reasonable that the amount of time required to make scale changes increased with part size and complexity. These two quantities affected the amount of time required to design the original part. It was also logical that the original time to the design the part and the time required to make scale changes were also correlated.

Table 2-9. Pearson Correlations for Computer Design Time for Scale Changes

	Years Experience	Structural	Size (dm^3)	Part Complexity	Computer Design Time
Computer Design Time for Scale Change	0.142	-0.212	0.909**	0.452**	0.759**

**p<0.05

Different linear correlation models were evaluated to determine the amount of computer design time required to make scale changes to existing parts. These linear regression models are shown in Table 2-10. Model one based the time required to make a scale change on the original time required to design the part. Note that the correlation coefficient in this model did not represent the ratio of design change time to original design time (these times were normalized by different means). Model two used both part size and complexity, and showed part complexity as negatively correlated with the design time required to make a scale change. This was not compatible with previous data. Model three used only part complexity, and showed part complexity as positively correlated with the design time required to make scale changes. The R^2 of this model was very low. Model four correlated part size with the amount of time required to make a scale change and had a high R^2. Because of its high R^2 and readily available input, model four was used to predict computer design time required to make scale changes to existing designs. The data predicted using model four and collected data from the surveys are plotted in Figure 7-3 (Appendix 7.2). A plot of standardized residuals verses predicted values for model four is also shown in Figure 7-4. This figure shows the error terms were evenly distributed and mostly independent of the predicted value.

Table 2-10. Linear Regression Models of Design Change Data[1]

Model	Constant	Size (dm^3)	Part Complexity	Computer Design Time	R^2	F-Stat
1	0.289 (0.188)	-- --	-- --	0.590 (0.108)	0.56	29.9
2	0.466 (0.379)	0.005 (0.001)	-0.117 (0.119)	-- --	0.82	52.6
3	-0.918 (0.739)	-- --	0.494 (0.208)	-- --	0.17	5.6
4	0.114 (0.125)	0.005 (0.000)	-- --	-- --	0.82	104

[1] Standard Errors in Parentheses

Data collected from formability engineers was analyzed to determine which part characteristics affected the time required to perform formability analyses. As with previous data, engineering effort was normalized by the mean engineering effort for the data set. Table 2-11 shows the Pearson correlation matrix for this data; statistically significant ($p \le 0.1$) relationships are detailed as follows. The time required to perform an iteration of a formability analysis was positively correlated with part complexity, part size, and whether or not the part is a surface part. Part complexity and part size were again positively correlated. The size of a part was also positively correlated with whether or not the part was a surface part.

Table 2-11. Pearson Correlation Matrix for Formability Engineer Survey Results

	Formability Engineering Time	Part Complexity	Size of Part	Years of Experience	Surface Part (1-yes)
Formability Engineering Time	■	0.764**	0.821**	-0.118	0.390**
Part Complexity		■	0.611**	0.147	0.237
Size of Part			■	-0.176	0.360**
Years of Experience				■	-0.151
Surface Part (1-yes)					■

**p<0.05

Four linear correlation models were evaluated for the engineering time required to perform a formability analysis. These models are shown in Table 2-12. Model one included part size, part complexity, and whether the part was a surface part. Whether or not a part was a surface part was not a statistically significant coefficient. Models three and four included part complexity and size, respectively. They did not have a R^2 as high as model two, which contained both. Given the higher R^2 and readily available inputs, model two was used to estimate formability effort in the following sections of this work. A plot of collected data verses predicted data can be seen in Figure 7-5 in Appendix Section 7.2. A plot of standardized residuals verses predicted values for model two is also shown in Figure 7-6. This figure shows the error terms to be evenly distributed and mostly independent of the predicted value.

Table 2-12. Linear Regression Models of Formability Data[1]

Model	Constant	Size (dm^3)	Part Complexity	Surface Part (1-yes)	R^2	F-Stat
1	-0.030 (0.203)	0.001 (0.000)	0.233 (0.072)	0.190 (0.207)	0.76	25.4
2	-0.022 (0.202)	0.001 (0.000)	0.235 (0.072)	-- --	0.76	37.9
3	-0.321 (0.257)		0.428 (0.077)	-- --	0.56	30.8
4	0.568 (0.107)	0.002 (0.000)	-- --	-- --	0.66	45.3

[1] Standard Errors in Parentheses

As previously mentioned, the aggregated and standardized nature of both the computer aided and physical validation stages did not allow for statistical analyses. Data for the individual tasks and complete projects were compared to standardized task list and found to be consistent (the sum of effort for individual tasks was relatively close to project effort). This data along with that collected about the cost of physical prototypes is used in Section 2.2.3 to complete the development model.

The effort required for fabrication engineering was split into expensed and capital portions. Contrary to the proposed hypothesis, engineering managers for fabrication said part characteristics had little effect on the expensed portion of engineering effort. Data from the thirteen stamped parts was analyzed to determine which characteristics affect die design time. As with the previous data, engineering effort for die design was normalized by the mean of the data set. Table 2-13 shows correlations between part characteristics and die design time. Die design time was positively correlated with part complexity, part size, and the number of dies required to form the part, as expected. Larger, more complex parts that require more dies should take more effort to design. The correlation between die design time and whether or not a part was a surface part was not statistically significant ($p \geq 0.1$). Part complexity was also positively correlated with part size (similar to design and formability data) and the number of dies. It is intuitive that more complex parts would require more dies to be formed. Part size and whether or not a part was a surface part were also found to have a statistically significant positive correlation. Data for die design time was both reasonable and consistent with previous data.

Table 2-13. Pearson Correlation Matrix for Die Engineering Survey Results

	Die Design Time	Part Complexity	Size of Part	Number of Dies	Surface Part (1-yes)
Die Design Time		0.834**	0.959**	0.462*	0.365
Part Complexity			0.718**	0.578**	0.205
Size of Part				0.275	0.391*
Number of Dies					-0.113
Surface Part (1-yes)					

*p<0.1
**p<0.05

Five linear regression models were analyzed to assess which part and project characteristics best predict die design time. These models are shown in Table 2-14. Model one includes all part and project characteristics. All are statistically significant except the surface part coefficient. Model two removed the surface part coefficient and had a R^2 of 0.97. However, the goal of the model was for use in the early stages of the development process when data such as the number of dies might not be available. Model three, which did not contain the number of dies, had a R^2 of 0.96. While part size and part complexity were correlated, model three performs markedly better than models four or five which use these characteristics separately. The higher R^2 and readily available inputs caused model three to be chosen, it was used to estimate stamping die design time in the subsequent sections of this work. A plot of collected data verses predicted data can be seen in Figure 7-7 (Section 7.2). A plot of standardized residuals verses predicted values for model three are also shown in Figure 7-8. This figure shows the error terms to be evenly distributed and mostly independent of the predicted value.

Table 2-14. Linear Regression Models of Die Design Data

Model	Constant	Size (dm^3)	Part Complexity	Number of Dies	Surface Part (1-yes)	R^2	F-Stat
1	-0.127	0.001	0.135	0.081	0.059	0.96	79.3
	(0.165)	(0.000)	(0.068)	(0.040)	(0.085)		
2	-0.094	0.001	0.137	0.074	--	0.97	112
	(0.153)	(0.000)	(0.066)	(0.038)	--		
3	-0.026	0.001	0.210	--	--	0.96	129
	(0.169)	(0.000)	(0.061)	--	--		
4	0.530	0.001	--	--	--	0.91	125
	(0.071)	(0.000)	--	--	--		
5	-0.833	--	0.581		--	0.67	25.2
	(0.381)	--	(0.116)		--		

[1] Standard Errors in Parentheses

Next, the data collected from assembly engineering experts was analyzed. Table 2-15 shows correlations between assembly characteristics and engineering effort. As hypothesized, engineering effort required for assembly was positively correlated with the number of parts in the assembly, the subassembly complexity, and the number of equivalent spot welds. These correlations were all statistically significant ($p \leq 0.1$). Engineering effort was negatively correlated with the number of joining methods; but was not statistically significant. Subassembly complexity was also positively correlated with the number of parts in the assembly and the number of equivalent spot welds. It was intuitive that more complex assemblies would have more parts and require more joining. The number of joining methods was also positively correlated with the number of equivalent spot welds.

Table 2-15. Pearson Correlation Matrix for Assembly Engineering Survey Results

	Engineering Hours Normalized	Number of Parts	Subassembly Complexity	Number of Equivalent Spot Welds	Number of Joining Methods
Engineering Hours		0.799**	0.649**	0.457**	-0.181
Number of Parts			0.349*	0.282	-0.228
Subassembly Complexity				0.475**	0.312
Equivalent Spot Welds					0.506**
Number of Joining Methods					

*$p<0.1$
**$p<0.05$

Linear regression was used to model the effects of assembly characteristics on assembly engineering effort. Six regression models are shown in Table 2-16. Model one contains five independent variables. While all coefficients were statistically significant, the number of joining methods coefficient was unexpectedly negative. This variable was dropped in model two and the results showed that the equivalent spot welds variable was not statistically significant. Model three contained part complexity and part size, while models four and five were functions of one of these variables only. Model three had an R^2 of 0.77, considerably higher than those of models four or five. This higher R^2 would have caused model three to be used, but the large negative intercept would have predicted negative values of assembly engineering for subassemblies with low complexity values. Model six contains part complexity and part size, but forces the intercept to the origin. Model six was used in this work to estimate assembly engineering effort. It should be noted that the higher R^2 for model six should not be compared with those models that contain an intercept. A plot of collected data verses data predicted using model three is shown in Figure 7-9 in Appendix Section 7.2. A plot of standardized residuals verses predicted values for model three can be seen in Figure 7-10. This figure shows the errors to be evenly distributed and mostly independent of the predicted value.

Table 2-16. Linear Regression Models of Assembly Engineering Data

Model	Constant	Number of Parts	Subassembly Complexity	Number of Equivalent Spot Welds	Number of Joining Methods	R^2	F-Stat
1	-0.194 (0.300)	0.054 (0.014)	0.308 (0.083)	0.002 (0.001)	-0.270 (0.102)	0.83	20.9
2	-0.621 (0.305)	0.073 (0.015)	0.255 (0.097)	0.001 (0.001)	-- --	0.76	17.5
3	-0.658 (0.294)	0.074 (0.015)	0.283 (0.087)	-- --	-- --	0.77	27.1
4	0.150 (0.203)	0.091 (0.018)	-- --	-- --	-- --	0.62	26.6
5	-0.486 (0.474)	-- --	0.435 (0.132)	-- --	-- --	0.38	10.9
6	-- --	0.070 (0.016)	0.119 (0.053)	-- --	-- --	0.88	65.4

[1] Standard Errors in Parentheses

2.2.3 Development Model

As with process-based cost models for fabrication and assembly, in the model of the development process, part characteristics were used to calculate intermediate outputs, and then used to calculate cost. In this model, lead time is calculated in addition to cost. The model presented in this thesis is similar to that of Alder, et al., in that it views the engineers in the development process as resources that are used to complete tasks [71]. This model however, estimated the engineering effort required to perform development functions based on part and assembly characteristics. This model also used empirical data to determine the amount of calendar time required to complete a given amount of engineering effort. The amount of engineering resources (number of engineers) available were then used to determine development stage lead time. Finally, the amount of overlap between development stages is used to determine project lead time. As noted previously, the sharing of parts can lower design cost and reduce lead time. Like the methodology used for fabrication and assembly costs, standalone, incremental, and shared costs were calculated. In addition, both standalone product lead time and incremental lead time for variants were estimated.

For the detailed design stage of the development process, part characteristics were used to predict computer design time. However as noted in Wallace and Hales, only a portion of the time required for design is spent doing actual design work. Other time is spent on related work tasks such as planning, reporting, retrieving and processing information, and other social or professional interactions [73]. The ratio of computer time to total design time required is referred to as design utilization, and is an input in the model. For this work the designer utilization input was calculated by averaging the ratio of computer design time to calendar time. In addition to direct labor cost required for designers, there were also overhead, which included management, building and other design related costs (not including computer hardware or software). A separate category related to design engineering was the cost of computer hardware and software. Workstations and software packages used for design can represent a significant portion of the total design cost. Data was collected about the yearly cost of both design computer hardware and software. Hardware and software costs for a part were determined by multiplying the ratio of total design time (not just computer design time) for a part to yearly designer time available by yearly software and hardware cost. This methodology assumed that each designer has his or her own hardware and software license. Lead time for the detailed design stage was determined by the number of designers available. This input was used to determine the total amount of design hours available for the product family being modeled. The ratio of total design time needed to total design time available determined lead time. This work assumed that only one designer works on each part; therefore the minimum lead time for the detailed design stage was the longest lead time for an individual part.

The cost and lead time for the formability engineering stage of the development process was modeled in a manner similar to that of the detailed design stage. The intermediate output of formability engineering time was used to determine cost and lead time. Both formability engineer utilization and the number of iterations required were inputs in the model. The averages of survey data for these two quantities were used. In addition to the individual computer and software costs, the cost of the mainframe on which formability simulations were run needed to be accounted for. This cost was derived from the yearly cost of the mainframe and the computation time required for a formability analysis. Since only one engineer can work on a part at a given time, the minimum lead time is again the longest lead time for a part (including iterations).

For the computer aided and physical validation stages of the development process, engineering effort and lead time averages for the various subassemblies were used. As mentioned above, due to the aggregated and standardized nature of theses stages, their cost has little variation for different products. Labor costs for this phase of the development process were calculated in the same way as those of the detailed design and formability engineering stages, but there are additional costs for both of these stages. For computer aided validation, these include the cost of the individual workstations, software licenses, and mainframe cost. For physical validation, the cost of producing and assembling physical prototypes must be incorporated into the estimation of development cost for the prototyping stage.

The process development stage was different in that it involved teams working on projects. For the stamping process, the number of engineering hours for expensed tasks was combined with the number of die engineering hours estimated from the regression model. Labor cost was calculated using the wage and overhead methods previously discussed. The total number of process engineers available and the maximum number of engineers working on a given part were specified as inputs. These inputs were used to determine the lower and upper limits of engineering lead time. This was analogous to the manner in which engineering lead time was calculated in the detailed design stage. The maximum number of engineers working on a part was used to determine a lower limit instead of assuming that only one designer could work on a given part.

The development of assembly processes was similar to the process development stage in that it involved teams performing the engineering work required for each subassembly. The number of engineering hours estimated using the linear regression model was again used as an intermediate output. Labor cost was calculated using the wage and overhead methods discussed. Engineering lead time was calculated in the same manner as the assembly engineering stage using inputs for the number of assembly engineers available and the maximum number working on a subassembly.

The engineering lead time for the entire development effort could be estimated once the engineering lead time for each stage of the development process was calculated. An input for the amount of the previous stage that must be completed before the subsequent stage begins was used to determine the amount of overlap between stages. This method was used in calculating the engineering lead time for the entire development effort as well as incremental lead times. The cost and lead time required for development as well as manufacturing and assembly cost were used in the following sections to analyze various product family strategies for automotive subassemblies.

3. Part Sharing for Different Architectures

To determine the effects of part sharing on cost savings, two alternative body-in-white architectures were analyzed. The first was a traditional stamped steel unibody. The second was a structure consisting mostly of tubes and cast nodes. In both cases, three variants were modeled and assumed to be produced at an annual production volume of 75,000. The analysis was limited to the development, fabrication, and assembly of the body-in-white. Section 3.1 details the analysis of the steel unibody architecture. Section 3.2 discusses the alternative tubular steel architecture, and the two cases are compared in Section 3.3. It should be noted that while the two architectures were functionally equivalent, the steel unibody architecture was from a vehicle make that was larger and more luxurious than that of the tubular steel architecture.

3.1 Traditional Stamped Steel Unibodies

In the case of the first architecture, three stamped steel unibody variants were analyzed. These bodies consisted of three models, from the same make, that shared parts. The first model, the entry-level vehicle for the make, was a four-door sedan (denoted as Entry). The second model was a crossover vehicle (denoted as X-Over). The final model, the high-end vehicle for the make, was also a sedan (denoted as High End). Part sharing between these vehicles is shown in Figure 3-1. Piece sharing is based on the number of parts, while the other sharing calculations are weighted by mass, piece cost, and investment. Percentage sharing was calculated using the methods detailed in Section 2.1.3. The total amount of sharing between all three variants, on a part basis was 13%. This amount of sharing decreased to 8% when weighted by the investment required to fabricate the part. The largest amount of sharing by all measures was between the entry-level vehicle and the high-end vehicle. This is not an unexpected result, as both vehicles were sedans. The amount of sharing between these two vehicles, even on an investment-weighted basis, was 19%. The lowest amount of sharing was between the entry-level vehicle and the crossover. These two variants were somewhat dissimilar.

The development cost for the three vehicles was estimated using the development model outlined in Section 2.2.3. Total development investment was amortized over the life of the product and divided by the production volume for each variant. This method of determining development costs allowed these costs to be compared to fabrication and assembly costs on a consistent basis (yearly cost of the body-in-white). These costs were calculated using three methods: standalone, shared, and incremental. Standalone cost was the cost of developing the vehicle while assuming that none of the other variants were developed. In this case, the variant was assigned the full cost of development for any part or subassembly contained in the vehicle. The shared cost method split the cost of development equally between all variants that contained that part or subassembly. Finally, the incremental method assigned the cost of a part or subassembly to the first vehicle developed that contained it (for the first vehicle this would be equal to the standalone cost). Any changes or additional parts were then assigned to the appropriate variants. This method determined the marginal cost of each additional variant. The incremental development costs for the three steel unibody designs are shown in Figure 3-2. Standalone and shared development costs are shown in Section 7.3.1 (on page 123) in Figure 7-11 and Figure 7-12 respectively.

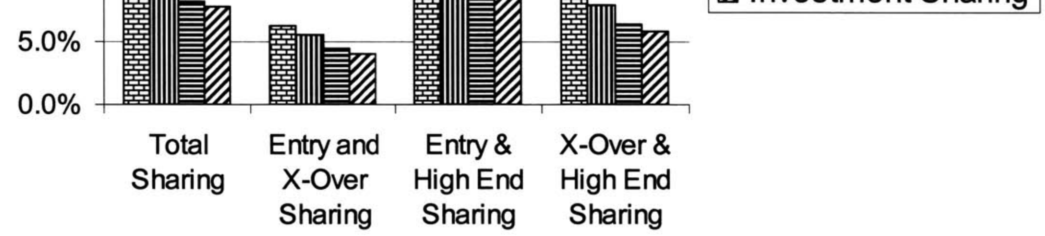

Figure 3-1. Sharing Among Steel Unibody Variants

Costs were broken down into categories representing various stages of the development process. The engineering required for the fabrication and assembly stages of the development process made up the majority of development costs. For standalone development costs of the entry-level vehicle, these two categories accounted for over

85% of the development costs. The sharing of parts between variants greatly reduced the aggregate development cost. The total shared development cost was 21% lower than that of the total standalone development cost. Of this savings, reduced fabrication and assembly engineering costs resulting from part sharing accounted for 94%. The effects of part sharing were also evident in the incremental development costs. This was the case for both variant vehicles, but is especially marked for the high-end vehicle. The incremental development cost for the crossover vehicle was 14% lower than when calculated on a standalone basis; the incremental cost of the high-end vehicle was over 50% lower. As was the case with the shared cost savings, over 90% of the savings arose from reduced costs for the fabrication and assembly engineering stages. Normalized development cost data can be found in Table 7-1 and Table 7-2 located in Section 7.3.1.

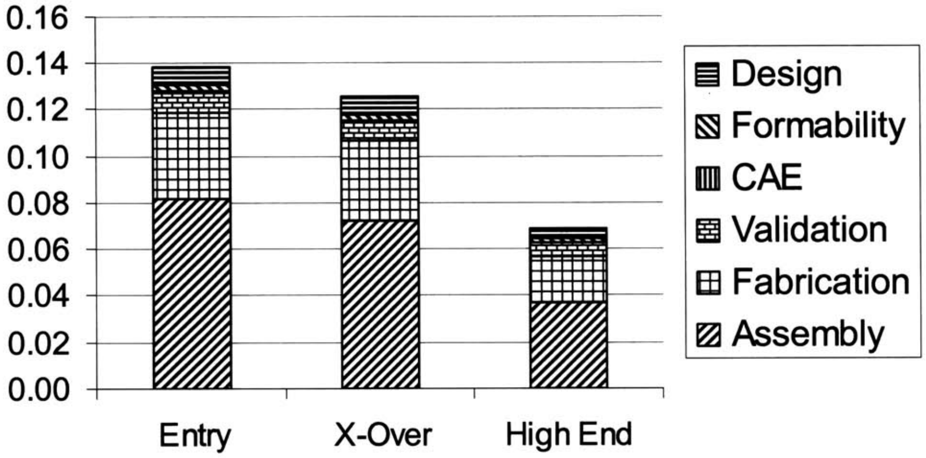

Figure 3-2. Incremental Development Costs for Steel Unibodies

In addition to determining development cost, the development model outlined in Section 2.2.3 was also used to determine the product development lead time. As with the development costs, lead time was calculated on both a standalone basis and an incremental basis. Also like development cost, lead time was broken down into categories for the various stages of the development process. Normalized standalone development cycle time for entry, crossover, and high end vehicles are shown in Section 7.3.1 in Figure 7-23, Figure 7-24, and Figure 7-25 respectively. Incremental development cycle time is shown below in Figure 3-3. In all cases, the validation and assembly engineering stages of the development process had the longest lead times. All three variants had similar standalone development lead times. The incremental lead time for the crossover vehicle was 7% less than the standalone lead time. For the high-end vehicle, the incremental development lead time was 17% less. Most of the incremental lead time savings came from the formability and assembly stages. The large overlap between the assembly and fabrication stages reduced the opportunity for timesavings in the fabrication engineering stage.

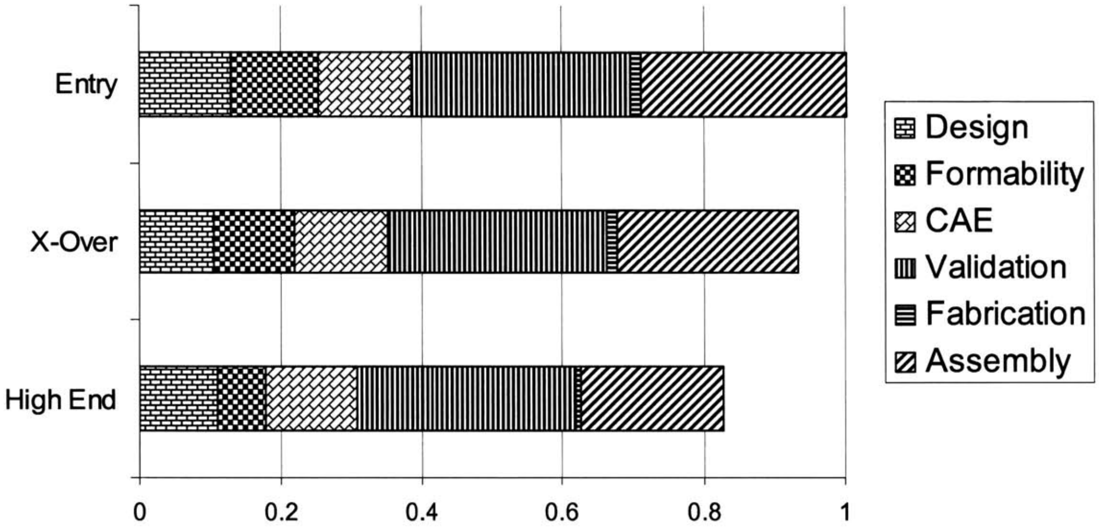

Figure 3-3. Incremental Development Time for Steel UnibodyVariant Vehicles

Fabrication costs for the constituent parts of the three vehicle variants were estimated using process-based cost modeling as outlined in Section 2.1. Costs were calculated in a manner analogous to those of the development process. Incremental fabrication costs are shown in Figure 3-4; while standalone and shared fabrication costs are shown in Figure 7-13 and Figure 7-14 respectively. Variable and fixed costs were split somewhat evenly. Variable costs accounted for 42% of the standalone cost for the entry-level vehicle. Materials and tooling made up the majority of the product cost in all three vehicles. These two cost categories made up over two thirds of the standalone cost of the entry-level vehicle. The total shared fabrication costs were 8% lower than the standalone fabrication costs. The large portion of variable costs and the assumption of full utilization for equipment limited the extent of cost savings from part sharing. If fixed costs alone were included, the shared fabrication costs for the three variants were 14%

lower than standalone costs. Over 80% of the cost savings arose from the sharing of tooling. The incremental fabrication costs for the crossover vehicle were 6% lower than the standalone crossover costs, or 11% if only fixed costs were considered. The incremental fabrication costs for the high-end vehicle were 19% lower than the standalone costs, or 33% when only fixed costs were taken into account. Most of the incremental cost savings came about from the reuse of tooling purchased for prior variants. The incremental tooling cost in the case of the high-end vehicle was 44% lower than the standalone cost; this accounted for 84% of the incremental cost savings. Normalized fabrication cost data can be found in Table 7-3 and Table 7-4 located in Section 7.3.1.

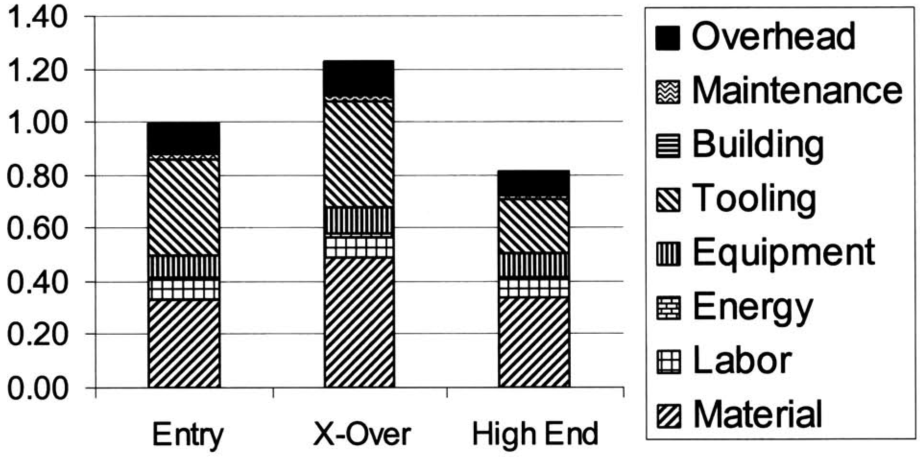

Figure 3-4. Incremental Fabrication Costs for Steel Unibodies

Assembly costs were estimated using the process-based cost modeling method detailed in Section 2.1.2. Standalone, shared, and incremental costs were calculated. Standalone and shared costs are shown in Section 7.3.1 in Figure 7-15 and Figure 7-16 respectively. Incremental assembly costs are shown below in Figure 3-5. Labor, tooling, and overhead make up the majority of assembly cost. For the standalone assembly cost of the entry-level vehicle, these three cost categories accounted for 87% of the assembly cost. The significant overhead cost is due to the large quantity of indirect laborers required for the various assembly stations. The total shared assembly costs were 23% lower than standalone assembly costs. When only fixed costs were included, cost savings rose to 25%. This less dramatic increase in cost savings, when looking at fixed costs, is due to the increased labor utilization that occurred in the shared assemblies. The incremental assembly cost of the crossover vehicle was 15% lower than the standalone cost, while the incremental assembly cost of the high-end vehicle was 54% lower. The majority of the cost savings in both the shared and incremental cases occurred in the labor, tooling, and overhead cost categories. In the case of shared costs, these three categories accounted for 95% of the savings. Normalized assembly cost data can be found in Table 7-5 and Table 7-6 located in Section 7.3.1.

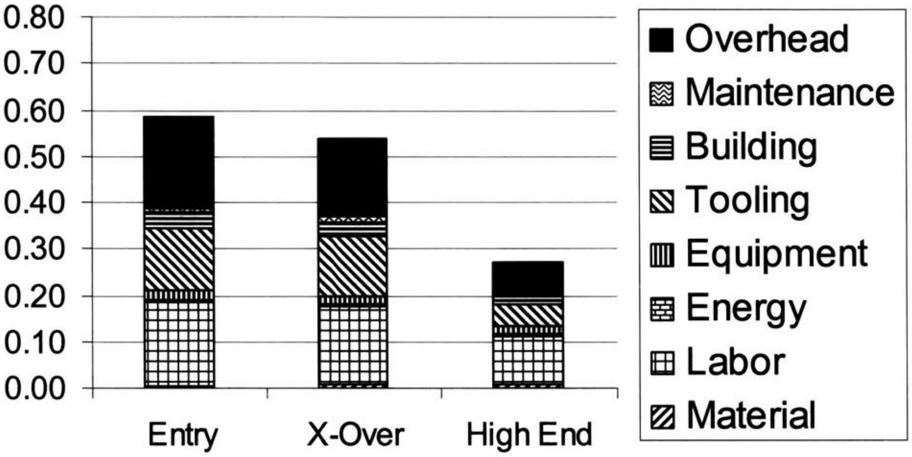

Figure 3-5. Incremental Assembly Costs for Steel Unibodies

The total costs and total fixed costs for the variant vehicle were also tabulated; these represent the sums of the previously discussed development, fabrication, and assembly costs. The total standalone cost and total shared costs are shown in Section 7.3.1 in Figure 7-17 and Figure 7-18 respectively. Incremental total costs are shown below in Figure 3-6. Standalone, shared, and incremental fixed cost are also shown in Section 7.3.1 in Figure 7-19, Figure 7-20, and Figure 7-21 respectively. For all three variants, fabrication accounted for the largest portion of the costs (around 60%), while assembly costs accounted for over 30%, and development making up the balance. The standalone and shared costs of producing combinations of variants are shown in Figure 3-7; Figure 7-22 in Section 7.3.1 shows the equivalent for fixed costs only. The total and fixed cost savings for the combinations of variants are shown in Figure 3-8. The largest cost savings occurred between the entry and high-end vehicles, these were 15% for all costs and 21% for fixed costs. The smallest cost savings occurred between the entry level and crossover vehicles, these were 5% for all costs and 6% for fixed costs. The overall cost savings, for all three vehicle variants, were 14% for all costs and 19% for fixed costs. This followed the trend of sharing among variants, where the entry and high-end vehicles had the most sharing and the entry and crossover vehicles had the least. However, more cost savings would be expected from sharing between the entry level and high-end vehicles, given that these two vehicles had almost twice as much sharing (by all measures) as that of all three variants. The incremental cost of the crossover vehicle was 9% less than the standalone cost, while the incremental cost of the high-end vehicle was 34% lower. The majority of the cost savings from sharing were in assembly, accounting for 54% of total cost savings, and fabrication, which accounted for 35%. Overall, the sharing among variants resulted in reduced cost and development lead time.

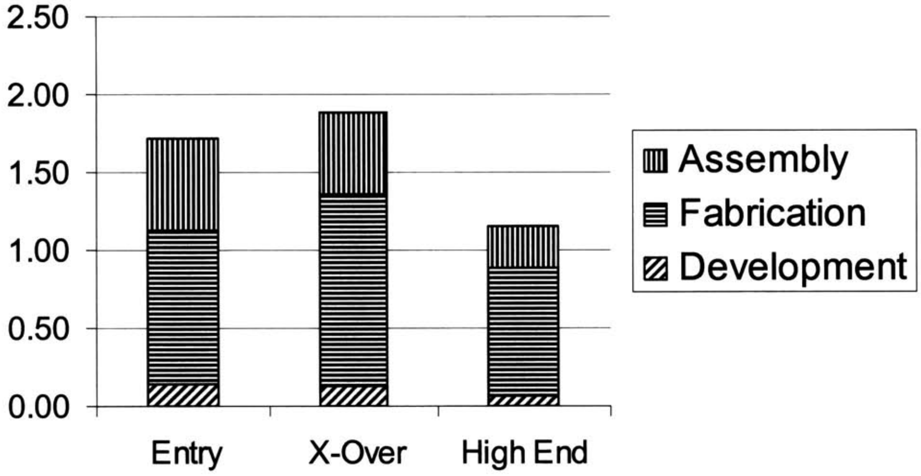

Figure 3-6. Incremental Total Costs for Steel Unibodies

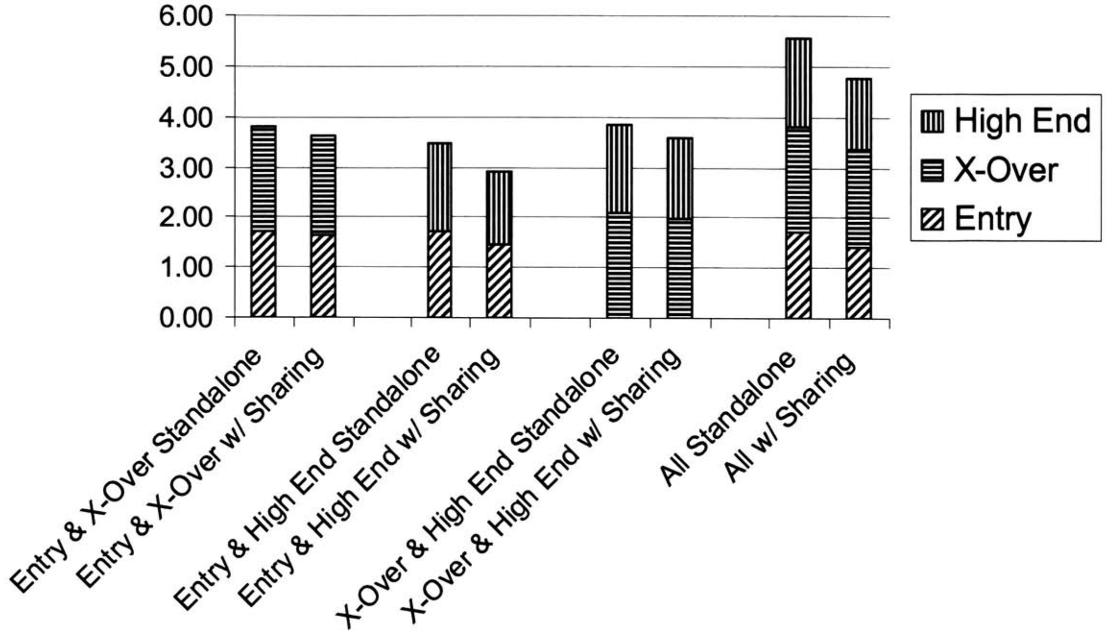

Figure 3-7. Steel Unibody Vehicle Costs - With and Without Sharing

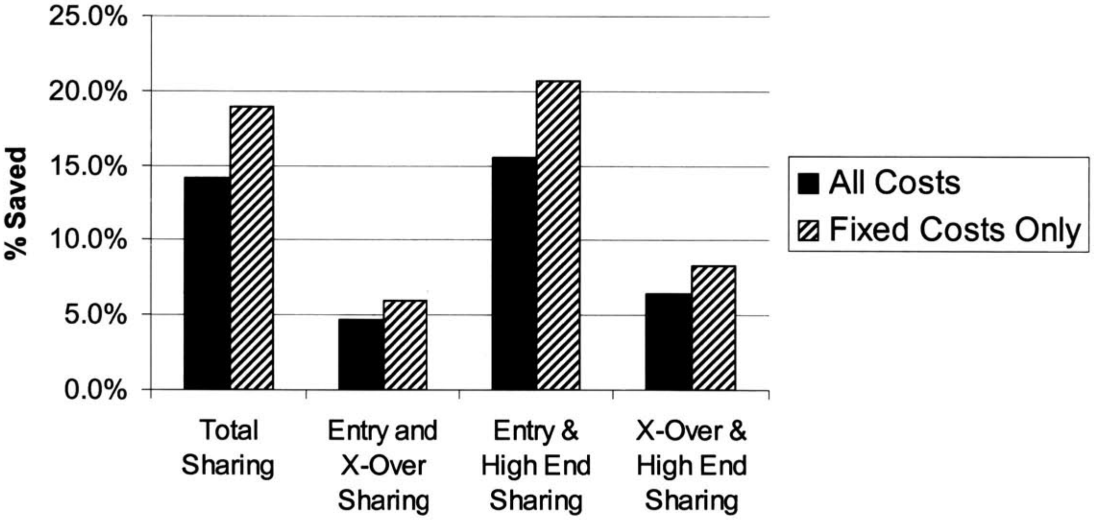

Figure 3-8. Cost Savings from Sharing Between Steel Unibody Vehicles

3.2 Alternative Tubular Steel Structure

In addition to the traditional stamped steel structure previously detailed, an alternative structural architecture was analyzed. This alternative structure consisted mostly of steel tubes and cast nodes. Unlike the previous example (the steel unibody), this architecture included several alternative fabrication processes: roll forming, hydroforming, steel casting, and composite molding. As with the previous example, the analysis was limited to the development, fabrication, and assembly costs for a body-in-white. Again, three vehicle variants were examined and all variants had an annual production volume of 75,000. The first vehicle was a mid-sized convertible; the second was a mid-sized sedan; and the final variant was a crossover vehicle. Part sharing was calculated as previously described, and is shown in Figure 3-9. The difference between sharing calculated using piece count, and that calculated using the weighted measures is marked. In the case of all three variants, piece count sharing was 46%, while sharing weighted by investment required for fabrication dropped to 13%. The most sharing occurred between the convertible and the sedan. It was expected that these two vehicles would share more parts than either would with the more dissimilar crossover.

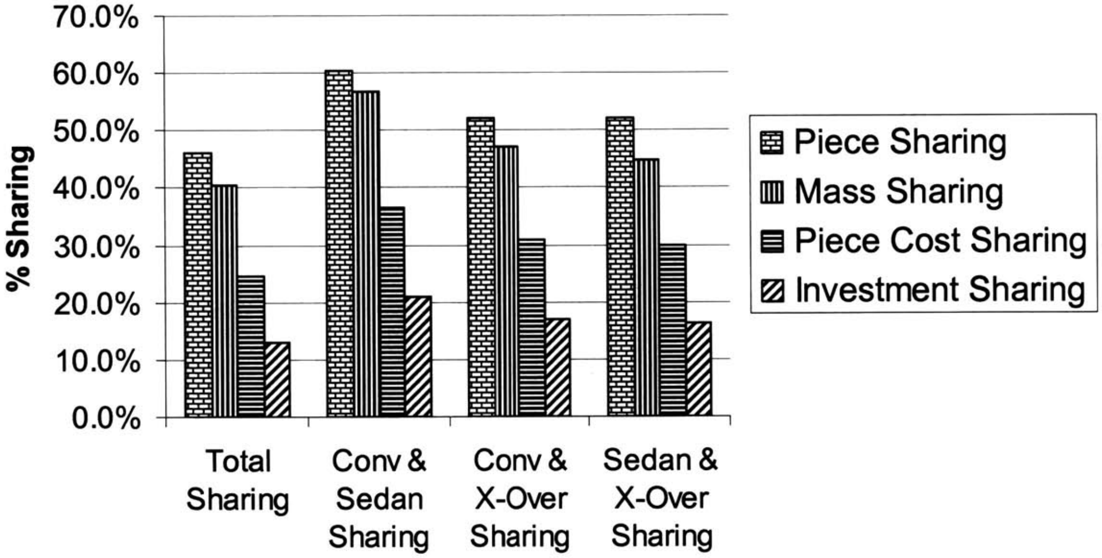

Figure 3-9. Sharing Between Tubular Steel Variants

The development costs for the vehicle were calculated using the method previously detailed. Again, these costs were calculated on a standalone, shared, and incremental basis. Incremental costs are shown in Figure 3-10, while standalone and shared development costs are shown in Figure 7-26 and Figure 7-27 (Section 7.3.2 on page 134) respectively. As with the previous example, fabrication and assembly engineering made up a majority of the development costs. In the standalone development costs for the convertible, these two cost categories accounted for 84% of the total. This percentage was similar to that of the steel unibody case. As with the steel unibody case, the sharing of parts greatly reduced the cost of development. The total shared development cost was 28% lower than the total standalone development cost. Reduced assembly and fabrication engineering costs accounted for over 90% of this savings. The incremental cost saving were also marked. For the sedan, the incremental development cost was 43% lower than the standalone cost, while for the crossover vehicle the incremental development costs were 41% lower. As was the case for the shared cost saving, reduced assembly and fabrication engineering cost accounted for a majority (90%) of the savings. Normalized development cost data can be seen in Table 7-7 and Table 7-8 in Section 7.3.2.

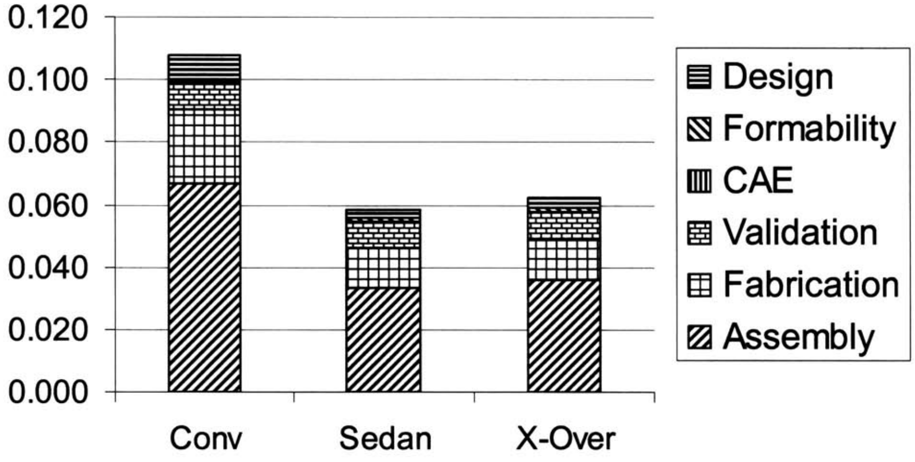

Figure 3-10. Incremental Development Costs for Tubular Steel Variants

As with the steel unibody case, development lead time was calculated in addition to development cost. Normalized standalone development times for the convertible, sedan, and crossover vehicle are shown in Figure 7-38, Figure 7-39, and Figure 7-40 respectively. Incremental development lead time is shown in Figure 3-11. As was the case with the steel unibody variants, the assembly and validation stages had the longest lead times. The incremental development time for the sedan was 5% shorter, while that of the crossover vehicle was 3% shorter, when compared to the standalone development lead times. For both the sedan and crossover vehicles, reduced lead time was mainly a result of reduced formability engineering lead time. Like the steel unibody cases, the overlap between the fabrication and assembly engineering stages mitigated the effects of sharing on the reduction of fabrication engineering lead time. Long lead time assemblies negated the effects of part sharing in reducing assembly engineering lead time.

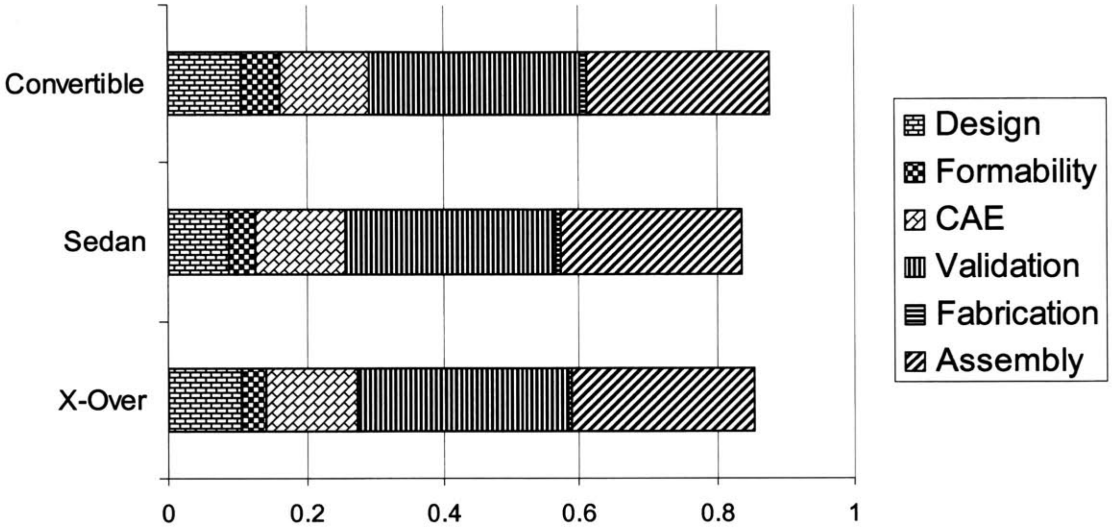

Figure 3-11. Incremental Development Time for Tubular Steel Variant Vehicles

Fabrication costs for the three vehicle variants were estimated using process-based cost modeling. Incremental fabrication costs are shown in Figure 3-12; while standalone and shared fabrication costs are shown in Figure 7-28 and Figure 7-29 respectively, in Section 7.3.2. Variable costs accounted for almost two-thirds of the fabrication costs; this was a significantly higher than for the steel unibody variants. Materials and labor accounted for over 60% of the total fabrication costs. The cost savings from sharing were minimal; the shared fabrication cost for all three variants was only 3% lower than the standalone fabrication cost. The cost savings from sharing increased to 7% when only fixed costs were included. The incremental fabrication cost for the sedan was less than 1% lower than the standalone cost. These savings are less than 3% when including only fixed cost. The incremental fabrication cost of the crossover vehicle was 7% lower than the standalone cost (17% for fixed costs only). The large portion of variable costs, the assumption of full utilization of equipment, and the low fraction of tooling cost explained the minimal cost savings from sharing. Most of the cost saving in the steel unibody case resulted from shared tooling. While the incremental tooling cost for the crossover vehicle was 36% lower than the standalone cost, tooling accounted for only 14% of the standalone cost of the crossover vehicle. This small fraction of tooling cost limited the effects of sharing in reducing fabrication costs. Normalized fabrication cost data can be seen in Section 7.3.2 in Table 7-9 and Table 7-10.

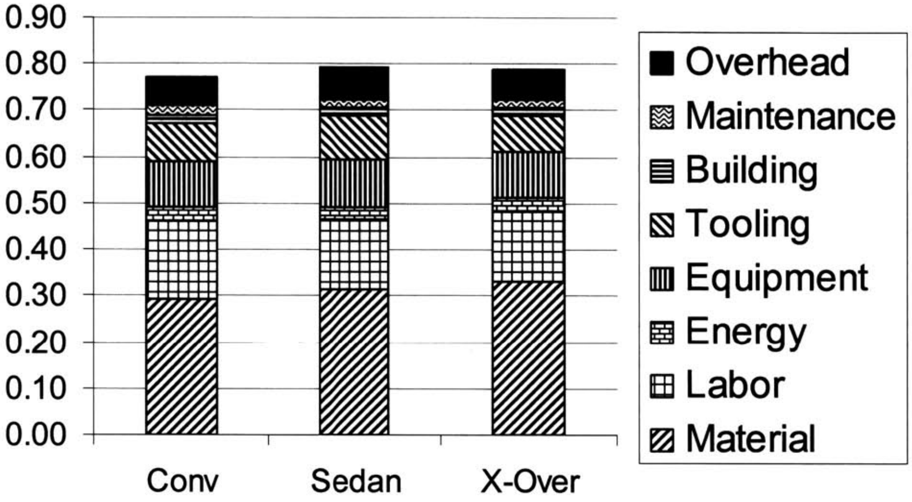

Figure 3-12. Incremental Fabrication Costs for Tubular Steel Variants

Assembly costs for the three tubular steel variants were estimated as described previously. Standalone and shared assembly costs are shown in Section 7.3.2 in Figure 7-30 and Figure 7-31 respectively. Incremental assembly costs are shown in Figure 3-13. Overhead and labor accounted for the majority of assembly costs in all three variants. In the case of standalone assembly costs for the convertible, these two categories account for almost 90% of the total assembly cost. The total shared assembly costs for all three variants were 11% lower than the sum of the standalone assembly costs. When only fixed costs were included, the shared costs were 20% lower. The incremental assembly costs for the sedan were 19% (33% when only taking account of fixed costs) lower than the standalone assembly costs. The incremental assembly costs of the crossover vehicle were 13% lower than the standalone costs; when only fixed costs were considered, they were 24% lower. The reduction of overhead costs accounted for over 70% of both the incremental and shared cost savings. Normalized assembly cost data can be seen in Section 7.3.2 in Table 7-11 and Table 7-12.

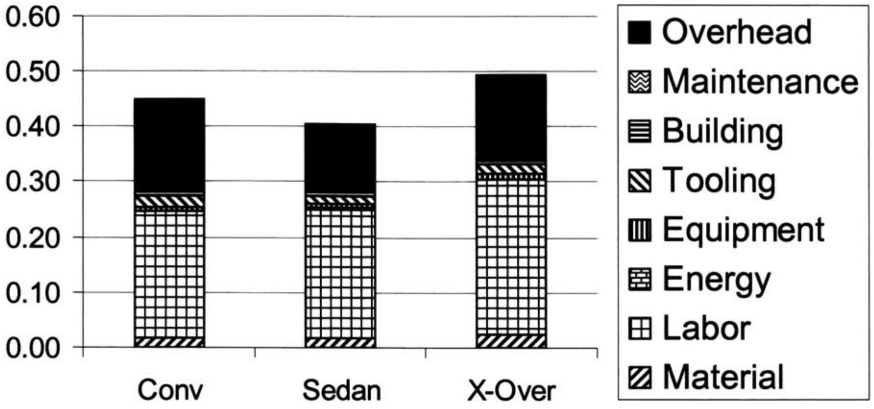

Figure 3-13. Incremental Assembly Costs for Tubular Steel Variants

Total costs were tabulated for the three tubular steel variants; these are the sums of development, fabrication, and assembly costs. Incremental total costs are shown in Figure 3-14, while standalone and shared total costs are shown in Section 7.3.2 in Figure 7-32 and Figure 7-33 respectively. Standalone, shared, and incremental total fixed cost are also shown in Section 7.3.2 in Figure 7-34, Figure 7-35, and Figure 7-36 respectively. For all three variants, fabrication accounted for the largest portion of the costs (around 57%). Assembly costs were the second largest portion, at around 35%. The standalone and shared costs of producing variant combinations are shown in Figure 3-15; Figure 7-37 shows the fixed costs for producing these variants. The total and fixed cost savings for vehicle variant combinations are shown in Figure 3-16. The incremental cost for the sedan was 10% lower than the standalone cost (20% when only considering fixed costs). The incremental cost for the crossover vehicle was 11% lower than the standalone cost (24% when only fixed costs were included). The largest cost savings between two variants occurred between the sedan and the convertible. The shared total cost of these two vehicles was 7% lower than the standalone cost (14% for fixed costs only). The least cost savings occurred between the sedan and the crossover vehicle; sharing in this case produced cost savings of less than 7% for total costs and 12% for total fixed costs. The overall cost savings from sharing was 8% for total costs and 15% for total fixed costs. As with the steel unibody case, the amount of savings from sharing between variant pairs follows the amount of sharing between those pairs. However, a larger percentage of saving occurred between all three variants, even though the amount of sharing for all three variants was considerable lower than for any of the variant pairs. This result was also similar to that of the steel unibody case. The majority of the cost savings from sharing were a result of lower assembly cost; this category accounted over 50% of the cost savings. Reduced development cost accounted for almost 30% of the savings, while reduced fabrication cost made up the balance. Overall, as in the previous case, part sharing resulted in reduced cost and development lead time.

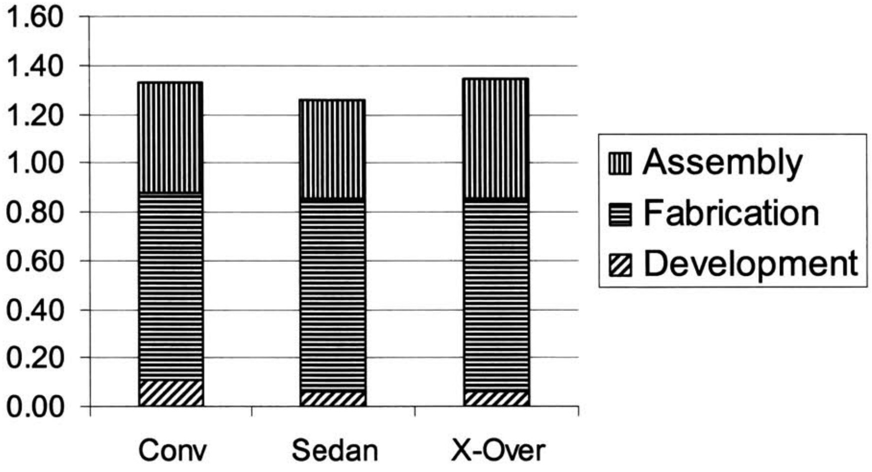

Figure 3-14. Incremental Total Costs for Tubular Steel Variants

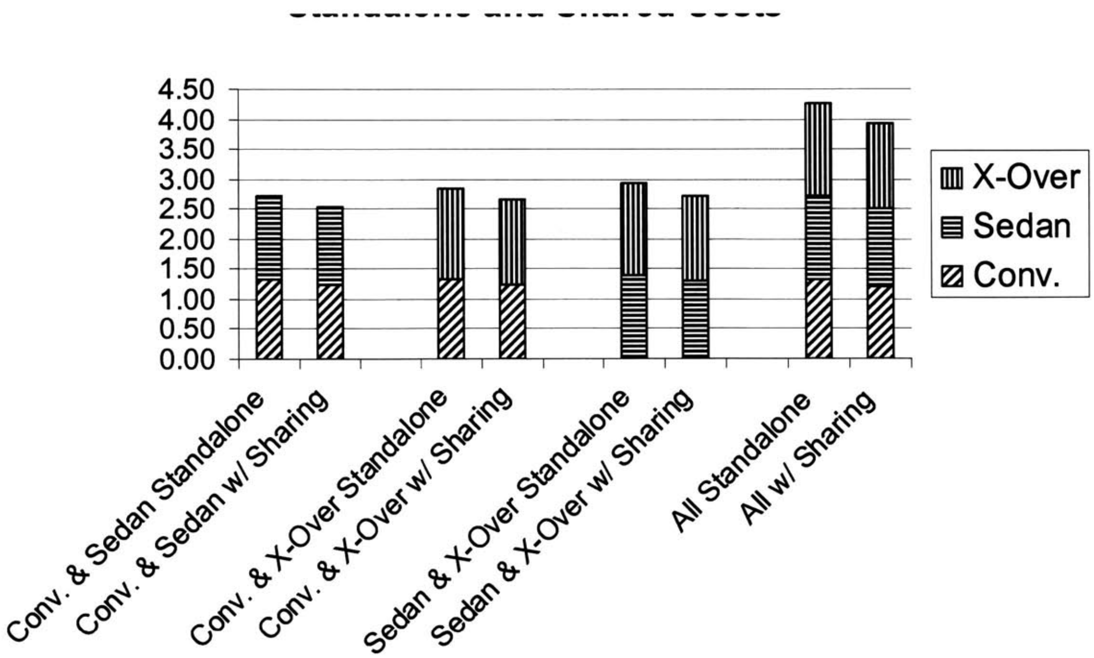

Figure 3-15. Tubular Steel Vehicle Costs - With and Without Sharing

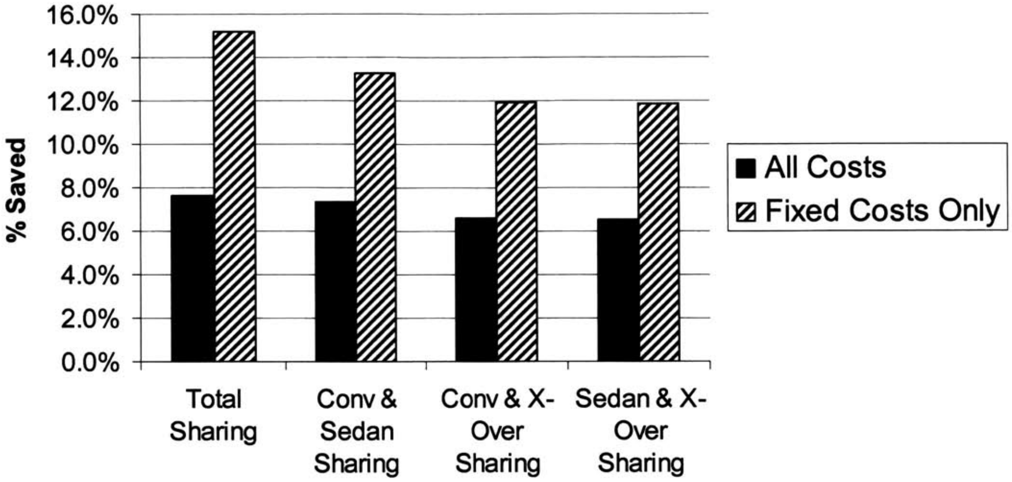

Figure 3-16. Cost Savings from Sharing Between Tubular Steel Variants

3.3 Comparing Body-in-White Architectures

Two functionally equivalent body-in-white architectures were analyzed to determine the effects of part sharing on development, fabrication, and assembly cost. The stamped steel unibody variants had much lower total sharing than the tubular steel variants. The part sharing between variant pairs was also markedly higher for the tubular steel variants. The difference between the amount of sharing when calculated by piece count and that weighted by investment was much larger for the tubular steel variants. This was due to the fact that the tubular variants did not share large investment parts, such as large composite molded or stamped steel panels. Most of the shared parts for the tubular variants were produced using lower investment production processes, such as tube bending or rollforming. For the stamped steel unibodies the discrepancy between sharing when calculated by piece count, and that weighted by investment was due to the uniqueness of large, variant defining parts, such as roofs and bodysides. This was reinforced by the much smaller differences between piece count sharing and mass-weighted sharing for the stamped steel unibodies as compared to that of the tubular steel variants (see Figure 3-1 and Figure 3-9).

The development costs for the stamped steel unibodies were approximately 35% higher than those of the tubular steel variants. The steel unibody variants had approximately twice as many parts, and many more subassemblies than the tubular steel structures. Many of the additional steel unibody parts were smaller and less complicated; this explained why development cost did not scale with part count. The cost breakdown between the various development stages was similar for both architectures. Part sharing resulted in development costs that were 28% lower for the tubular steel vehicles. This was approximately a third higher than the percentage saved from sharing in the steel unibodies. However this was less than expected, given the much higher amount of sharing between the tubular steel variants. The tubular steel variants had almost four times as much sharing when calculated by piece count, and over 65% more sharing when weighted by fabrication investment. For some tubular steel variant parts, additional development was required, even though these parts were fabricated using the same tooling and machinery[7]. This explained some of the discrepancy between the expected and actual cost savings from sharing for the tubular steel architecture. The total standalone development lead time for the steel unibody vehicles was 14% longer than that of the tubular steel vehicles. The total incremental lead time for the unibody vehicles was only 8% longer. The incremental development time for the high-end steel unibody vehicle was shorter than the incremental development lead time for the tubular steel crossover vehicle.

The fabrication costs for the stamped steel unibodies were almost 40% higher than those of the tubular steel variants. Again increased part count explained some of this variation, but the breakdown of fabrication costs for the two variants were very different. Materials were one of the largest cost categories in both cases (almost 40%). In the case of the tubular steel architecture, labor made up 19% or the fabrication costs, compared with 6% for the steel unibody variants. For the steel unibody architecture, tooling cost accounted for 36% of fabrication cost, this compared with 13% for the tubular steel variants. The cost savings from part sharing for the steel unbodies was 8% lower than the standalone fixed costs, this was considerably higher that the 3% savings for the tubular steel variants. This difference was explained by the large discrepancy in tooling required between the two architectures. Since the vast majority of cost savings in fabrication arose from shared tooling, the tubular architecture's lower tooling costs limited the

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[7] Parts were considered shared if they used the same fabrication tooling, regardless of additional design or finishing.

opportunity for these savings, even though the tubular architecture had much higher sharing.

The total standalone assembly costs for the steel unibody variants were over 20% higher than those of the tubular steel structures. The larger number of parts and subassemblies required for the steel unibody variants explained some of this cost differential. But as with fabrication, the cost breakdowns for the two architectures were very different. While labor accounted for over half of the assembly cost in for the tubular steel variants, it made up just over 30% of the cost of the steel unibody variants. Tooling made up 23% of the assembly costs for the steel unibody vehicles; it accounted for only 4% for the tubular steel vehicles. The total assembly cost savings from part sharing for the steel unibody architecture was 23%, for the tubular steel variants they were 11% lower. As was the case with fabrication, a large portion of the assembly cost savings arose from shared tooling. The tubular steel architecture's limited tooling cost reduced the effects of part sharing on reduced assembly costs.

The total standalone costs (sum of development, fabrication, and assembly) for the steel unibody architecture were 30% higher than those of the tubular steel architecture. However, the total shared costs of the steel unibody architecture were only 21% higher. The cost category breakdowns for the two architectures were similar; fabrication costs accounted for approximately 60%, while assembly cost accounted for over 30%. For both architectures, the reduction of assembly costs accounted for over half or the total cost savings. In the case of the steel unibody variants, the reduction of fabrication costs (mostly from shared tooling) represented 35% of the cost savings. For the tubular steel vehicles, fabrication cost savings made up only 20% of the total cost savings, and development accounted for 28%. The reduced amount of tooling used for the tubular steel vehicles lowered the overall cost of these variants, but it also reduced the opportunity for cost savings in fabrication and assembly. This enhanced the importance of cost savings derived from the development process. This lack of savings from shared tooling partially explained the less than expected cost saving for the tubular steel architecture. The tubular steel architecture had 66% more sharing (when weighted by investment) than the steel unibody architecture. The total fixed cost savings from sharing for the tubular steel vehicles was only 2% higher than that of the steel unibody architecture.

Two important strategic variables for a development project are the production volume and product life. As previously mentioned, production volume affects the role of fixed costs on piece cost, for higher production volumes fixed costs are spread over more units thus reducing piece cost. Product life is the number of years a product is expected to be produced; it is also the number of years over which tooling and development costs are amortized. Shorter product lifetimes result in higher yearly costs for tooling and development. The effects of product life and production volume on cost savings, for the two alternative architectures, are shown below. Figure 3-17 shows cost savings for the unibody, while Figure 3-18 shows cost savings for the tubular structure. The production volume is the annual production volume per variant. As expected, as production volume and product life decrease, cost savings from sharing increased in both cases. In the case of the steel unibody, sharing produced cost savings greater than 5%, even at production volumes as high as 150,000 per year, with a product life of ten years. For the tubular body, the maximum production volume (with ten year product life) with cost savings greater than 5% was 90,000 per year, per variant. However in the very low production volume range (around 10,000 per year) the tubular body produced higher cost savings than the unibody design at all product lifetimes. Cost saving decreased faster for the tubular structure vehicle as a function of both product life and production volume. The large portion of variable (mostly material costs) costs for the tubular design reduced the opportunity for cost savings. This explained the large cost saving for very low production volumes. At these low volumes, the role of fixed costs for the tubular design was greater, and thus the opportunity for sharing was greater as well. The large portion of tooling cost for the unibody design made cost savings possible even at high production volumes and longer product lifetimes. The amount of savings from part sharing, and thus the preferential architecture was dependent on the expected production volume and product lifetime.

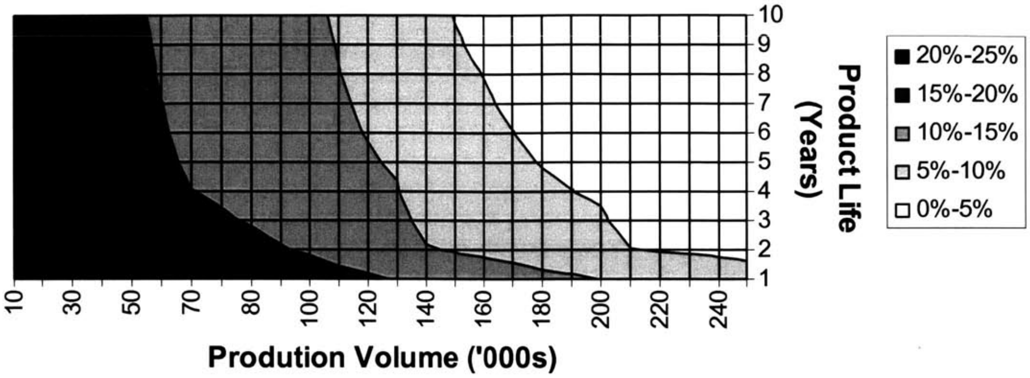

Figure 3-17. Unibody Cost Savings Sensitivity for Annual Production Volume and Product Life

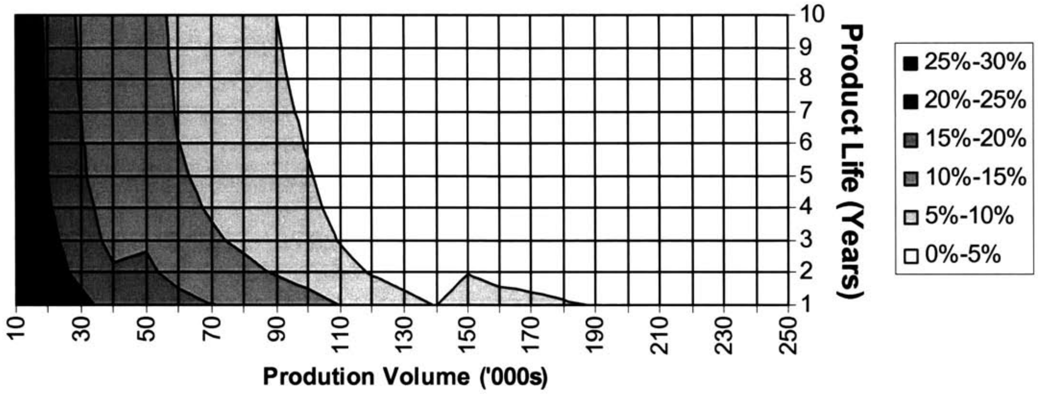

Figure 3-18. Tubular Body Cost Savings Sensitivity for Annual Production Volume and Product Life

4. Parts Consolidation

To determine the effects of parts consolidation on total costs (development, fabrication, and assembly) and cost savings from part sharing, two alternative instrument panel (IP) beam designs were analyzed. The steel IP beam (denoted Steel IP) consisted of a tubular structure with over two-dozen brackets attached. The other design was a die cast magnesium structure (denoted Mag IP) with four additional brackets. In both cases the costs of development, fabrication, and assembly were modeled. Section 4.1 discusses the base case comparison between the alternative designs, while alternative scenarios are detailed in Section 4.2.

4.1 Base Case

As previously mentioned, the steel IP beam consisted of numerous brackets attached to an underlying tubular structure. To obtain a functionally equivalent die cast design required a complex magnesium die casting. In addition to the original IP beams, additional variants that were 10% longer and had several different connections were also modeled. In the case of the steel IP beam, it was assumed that the two variants shared several brackets and a portion of the tubular structure. In the case of the magnesium IP beam, it was assumed that the main die castings were unique, but that brackets were shared. Sharing metrics for the two beam types, calculated using previously detailed methods, are shown in Figure 4-1. On a piece count basis, the sharing for the magnesium beams is higher than that of the steel beams. The sharing of the four brackets, with only unique castings explained this high level of sharing. In all the cases using weighted sharing measures, the steel IP beam had considerably more sharing that the magnesium versions. The steel variants had 51% sharing, when weighted by fabrication investment, compared to 6% for the magnesium beams. In both the steel and magnesium cases, the amount of sharing weighted by investment was slightly higher than that weighted by piece cost and mass. This was due to the high prevalence of sharing among small stamped parts. The investment required to fabricate these small parts represented a larger portion of total investment, than these parts represented of the total mass or piece cost.

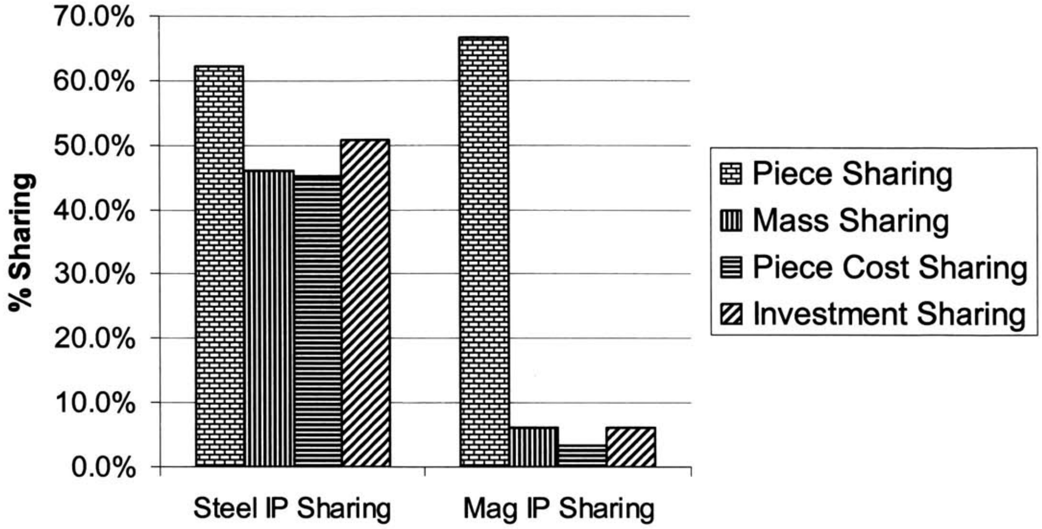

Figure 4-1. Sharing Between IP Beams

The development costs for the two sets of IP beam variants were calculated using previously detailed methods. Incremental development costs for the two sets of variants are shown in Figure 4-2; standalone and shared development costs are shown in Figure 7-41 and Figure 7-42 respectively (in Section 7.4 on page 145). The standalone development costs for the steel IP beam were over six times higher than those of the magnesium IP beam. This difference was due mainly to the larger number of parts, and more complex assembly process, required for the steel IP beam. While the development costs for the die cast magnesium structure were three times greater than those of the tubular steel structure, this was not enough to counter the larger number of parts in the steel IP beam design. The proportions of costs between the various stages of the development process were similar for the steel and magnesium beams. In both cases, assembly and fabrication engineering accounted for over 90% of the costs. The shared development costs for the two steel variants were 43% lower than the standalone costs; the shared development costs for the magnesium variants were 40% lower. The incremental cost for the second steel variant was 86% less than its standalone cost, while the incremental cost for the second magnesium variant was 79% lower. While the overall development costs of the magnesium IP beams were much lower than those of the steel IP beams, the distribution of costs amongst development stages and the amount of savings from sharing were similar for the two designs. Normalized development cost data for the IP beams is shown in Table 7-13.

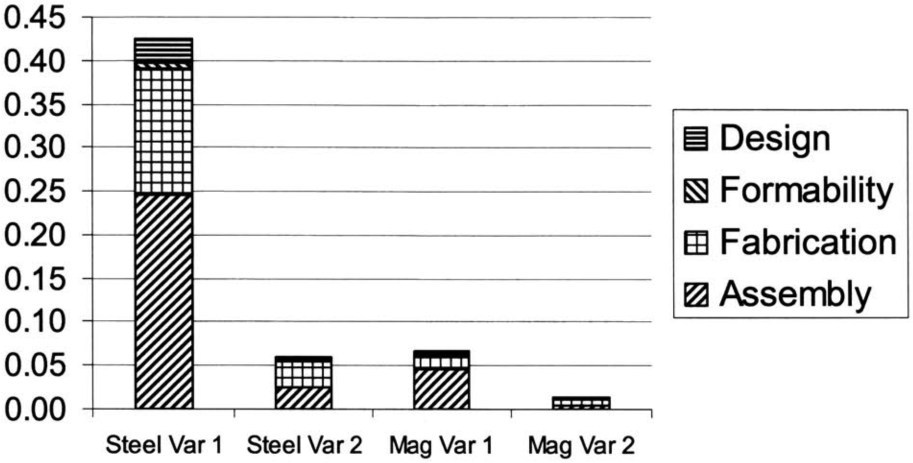

Figure 4-2. Incremental Development Costs for IP Beams

In addition to development costs, development lead time was also modeled for the two IP beam designs. Figure 4-3 shows the standalone lead times for the first variants, and the incremental lead times for the second variants, of both the steel and magnesium designs. The standalone lead time for the original steel IP beam is over 250% longer than that of the standalone magnesium beam. This difference was due mainly to the increase assembly engineering lead time required for the steel design. The incremental development lead time for the steel beam was 19% shorter than that of the magnesium version. This was due to the longer detailed design time required for the main magnesium casting.

Fabrication costs were modeled using process-based cost modeling techniques. Incremental fabrication costs for the two alternative designs are shown in Figure 4-4; standalone and shared fabrication costs are shown in Figure 7-43 and Figure 7-44 respectively. The standalone fabrication cost of the first magnesium beam variant was 54% higher than that of the steel beam. The cost of materials, in the case of the magnesium beam, accounted for a large portion of the differential. The cost of materials for the magnesium beam was greater than the entire cost of the steel beam. In contrast, tooling costs for the steel beam were almost four times higher than those of the magnesium beam. This was due to the larger number of parts in the steel beam.

Although the magnesium design contains a large complicated magnesium casting, the tooling cost for this did not outweigh that of the large number of small stamped steel parts. The shared fabrication costs of the two steel beams were 12% lower than the standalone fabrication costs. For the magnesium beams, sharing reduced fabrication costs by less than 1%. The incremental fabrication cost for the second steel IP beam was 12% lower, while the incremental cost of the magnesium beam was just over 1% lower. Normalized fabrication cost data for the two IP beam design is shown in Table 7-14.

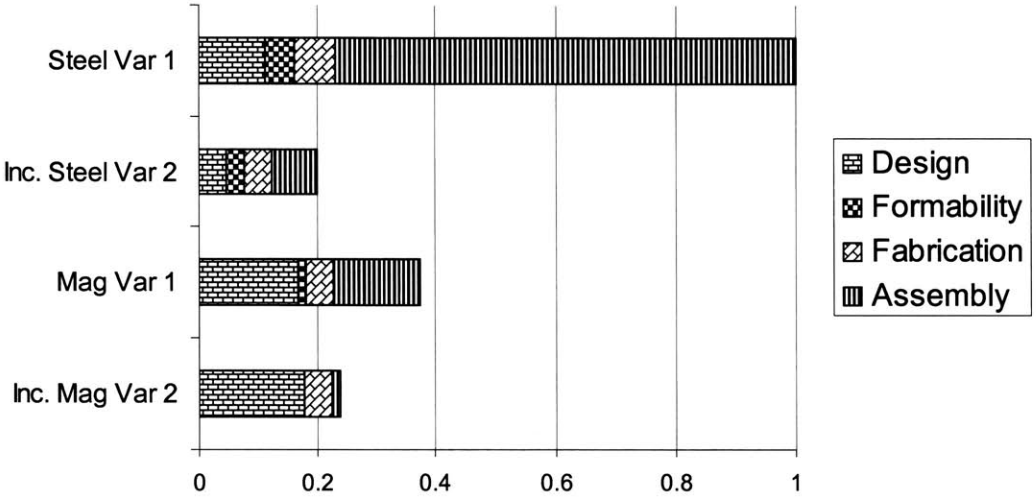

Figure 4-3. Development Lead Time for IP Beams

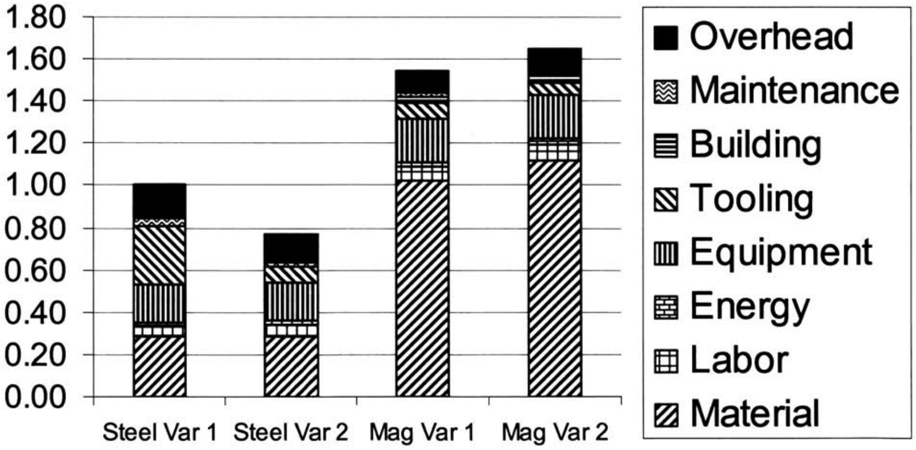

Figure 4-4. Incremental Fabrication Costs for IP Beams

Assembly costs for the two beam designs were modeled using previously detailed methods. Incremental assembly cost for the two alternative IP beam designs are shown in Figure 4-5. Standalone and shared costs are shown in Figure 7-45 and Figure 7-46 respectively. The assembly costs for the magnesium beam are 49% lower than those of the steel beam. This is due to the reduced amount of joining required for the magnesium beam. In both cases, overhead, tooling, and labor are the largest cost categories. The shared assembly costs for the steel variants were 33% lower than the standalone costs. For the magnesium variants, they were 50% lower. The incremental assembly cost for the second steel variant was 67% lower than its standalone cost; for the second magnesium variant it was almost 100% lower. Due to the limited amount of joining required for the magnesium variants, the assembly equipment was extremely underutilized for one variant. This made the marginal assembly cost of the second magnesium variant almost zero. Normalized assembly costs for the two designs are shown in Table 7-15.

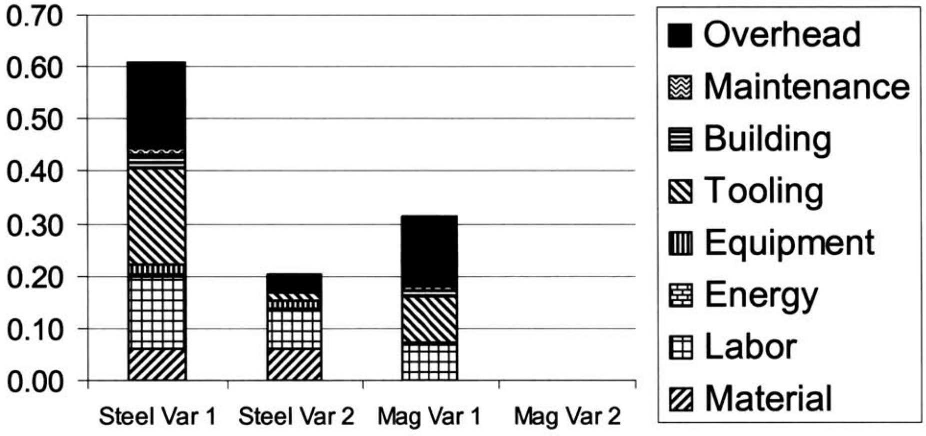

Figure 4-5. Incremental Assembly Cost for IP Beams

The total costs (sum of previously detailed development, fabrication, and assembly costs) for the two alternative IP beam designs were also analyzed. The incremental total costs for the two IP beam designs are shown in Figure 4-6. Standalone and shared total costs are shown in Figure 7-47 and Figure 7-48 respectively. Standalone, shared, and incremental total fixed costs are shown in Figure 7-49, Figure 7-50, and Figure 7-51 respectively. The total standalone cost for variant one of the magnesium IP beam was 5% less than that of variant one of the steel beam. The total standalone cost of the second magnesium IP beam was approximately equal to the second steel IP beam. The marked increase in magnesium beam cost was due to the increased material required in the second beam (which was 10% longer). The total shared costs of the two steel IP beam variants were 25% less than their standalone costs; for the magnesium beams shared costs were 10% less (see Figure 4-7). The incremental total cost of the second steel IP beam variant was 50% lower than its standalone cost. The incremental total cost for the second magnesium variant was 19% lower. For the steel IP beams, the majority of the cost savings from shared parts was derived from reduced development costs (39% of total savings); reduced assembly costs accounted for 36% of the savings, with reduced fabrication cost making up the balance. For the magnesium IP beams, reduced assembly costs accounted for 76% of the cost savings, while reduced development costs accounted for 17%. While the standalone costs for both magnesium beam variants were 3% lower than the standalone costs for the steel beams, the shared cost for the magnesium beams were 17% higher. This was due to the lack of fabrication cost savings from part sharing for the magnesium IP beams and the high cost of primary magnesium for the die castings. The standalone total fixed costs for the two magnesium IP beam variants are 49% lower than those of the steel variants, while the shared magnesium beam fixed costs are 41% lower. While the standalone cost of a magnesium IP beam is slightly less than that of its steel counterpart, when variants are derived from the original product, the total shared costs of the steel IP beams can be considerably less.

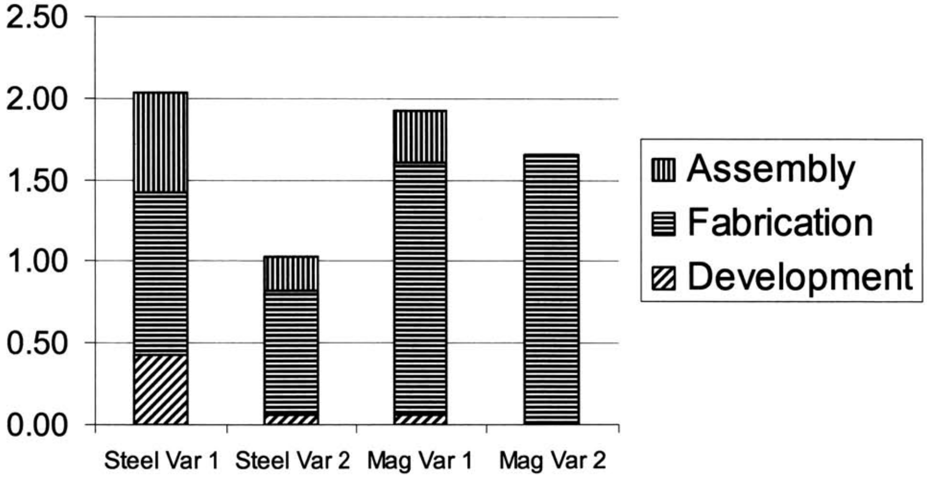

Figure 4-6. Incremental Total Costs for IP Beams

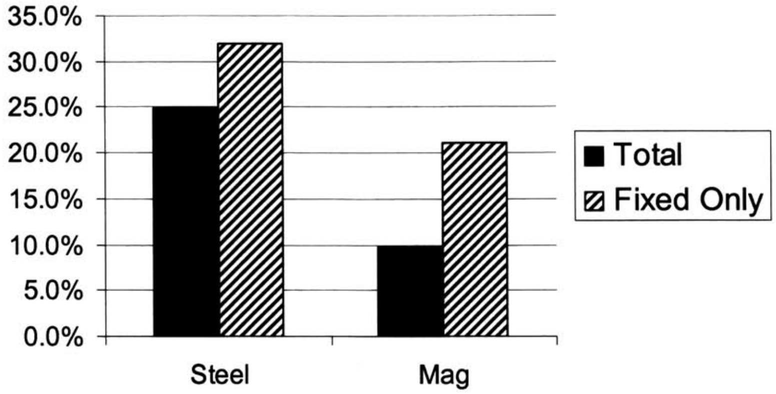

Figure 4-7. Cost Savings from Sharing for Alternative IP Beam Designs

4.2 Alternative Scenarios

With regard to manufacturing cost, the effects of production volume for sheet-metal stamping and die casting are significantly different. As can be seen from Figure 4-4, stamping costs are dominated by fixed investments in tooling, while material costs drive die cast costs. These characteristics lead to higher economies of scale for stamped designs relative to analogous die cast part. To understand the impact of these differences, the effects of product life and production volume on cost savings were explored for the steel and magnesium designs. These results are shown below in Figure 4-8 and Figure 4-9, respectively. As expected, cost savings increased as production volume and product life decreased, for both the magnesium and steel designs. In the low production volume, short product lifetime range, the steel IP beam had cost savings of over 45%. The highest level of cost savings for the magnesium design was 30%; this also occurred in the low production volume, short product lifetime area of the plot. The steel IP beam had much higher part sharing by all metrics than the magnesium IP beam. The largest differences between the cost savings for the two IP designs were in the low production volume region and the short product lifetime region. In these areas, the cost savings for the steel IP beam were over 20% higher than those of the magnesium beam. For the steel IP beam, the large portion of tooling cost increased the opportunity for reduced costs from part sharing. In the case of the magnesium IP beam, material cost accounted for a large majority of total cost and thus minimized the ability to reduce costs from part sharing. While the low production volume, short product lifetime conditions led to increased cost savings for the magnesium IP beam, the lower amount of sharing (according to weighted metrics) and higher portion of material cost reduced the amount of savings. This led to large differences in cost savings between the two designs under low volume, short product lifetime scenarios.

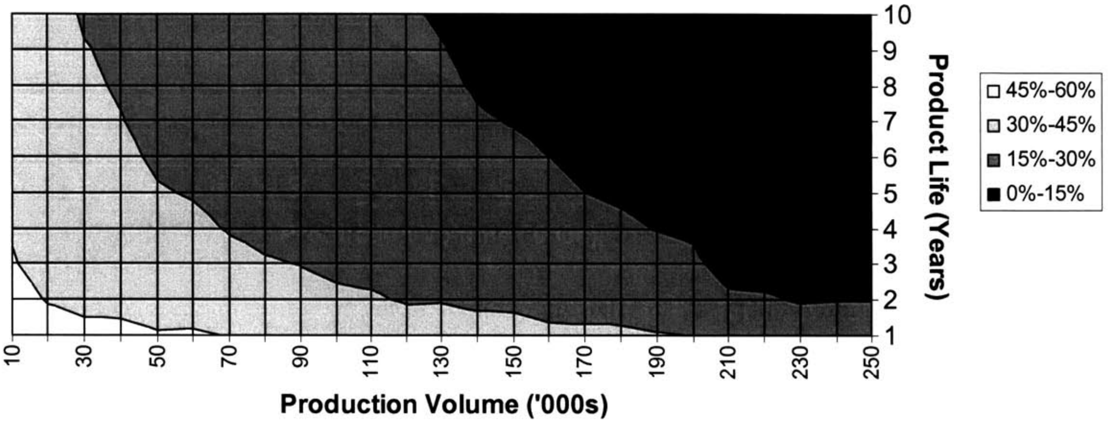

Figure 4-8. Steel IP Beam Cost Savings Sensitivity to Production Volume and Product Life

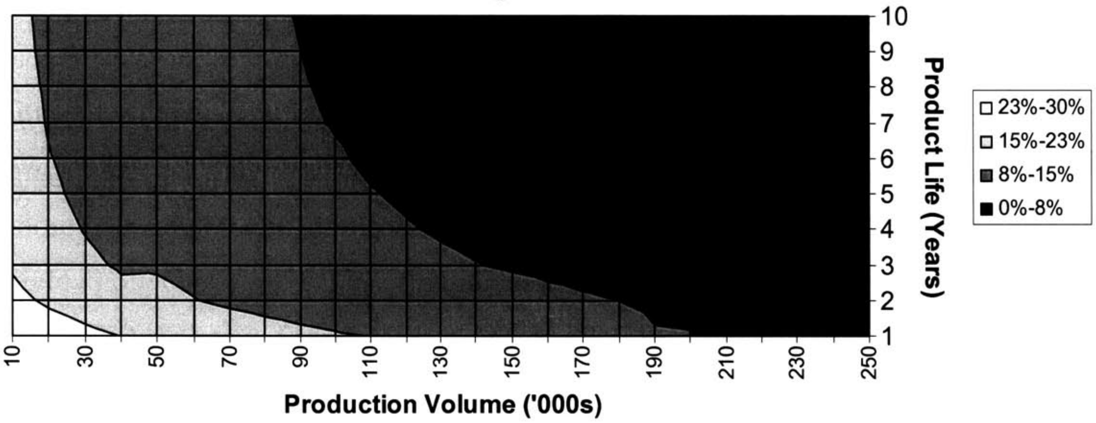

Figure 4-9. Magnesium IP Beam Cost Savings Sensitivity to Production Volume and Product Life

In addition to its ability to consolidate parts, magnesium is used for its ability to reduce weight [30]. In cases where the cost of a magnesium part is higher than an alternative design, it may still be preferred, because it weighs less. For this to be true, a product designer would have to exhibit some positive value for weight savings – a characteristics which over limited ranges could be expressed as a single value with units of \$ / kg saved. Given the results of the model, it is possible to compute the value of the weight savings which would be necessary for a designer to prefer the more expensive, but lighter magnesium design. This requisite value of the weight savings for the variant pairs of IP beams was calculated as:

$$V = \frac{C_{Stl} - C_{Mg}}{m_{Stl} - m_{Mg}} \tag{4-1}$$

where V is the requisite value of the weight savings, C_{Stl} is the cost of the steel IP beams, C_{Mg} is the cost of the magnesium IP beams, m_{Stl} is the mass of the steel IP beams, and m_{Mg} is the mass of the magnesium IP beams. Such a figure is only meaningfully defined for cases where the lighter design costs more than the alternative. The requisite value of the mass savings as a function of magnesium price and production volume is shown for both the standalone and shared cases in Figure 4-10 and Figure 4-11, respectively. For the standalone case, the black area represents a positive value required for the mass savings. In all other areas of the plot, the magnesium beams cost less than their steel counterparts. The economies of scale for the steel IP beam, which comprised a majority of steel stampings, caused the mass savings premium to be positive at higher production volumes. However, once the price of magnesium dropped below \$2.85 per kilogram, the standalone magnesium IP beams were less expensive than the steel IP beams at all production volumes. It should be noted that between April 2003 and March 2004 the spot price of magnesium rose from \$2.20 to \$3.35 per kilogram [92, 93]. When shared costs for the two IP beam designs were used, the mass savings premium was positive over a larger range of magnesium prices and production volumes. In the shared context, the magnesium design is less expensive than the steel design at all production volumes, when the magnesium price is below \$2.55 per kilogram. The cost savings from part sharing markedly increased the production volume and magnesium price ranges for which the mass savings premium was positive.

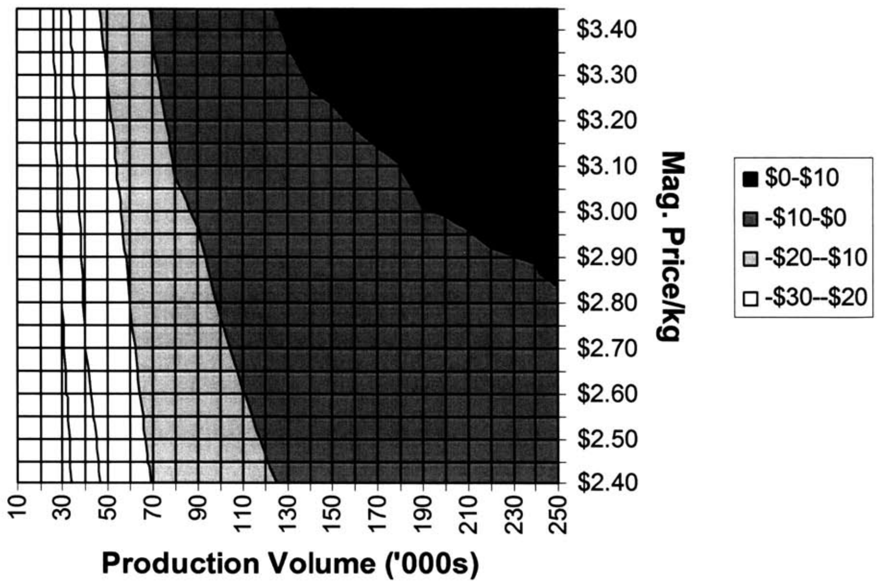

Figure 4-10. Mass Savings Value Sensitivity to Magnesium Price and Production Volume - Standalone

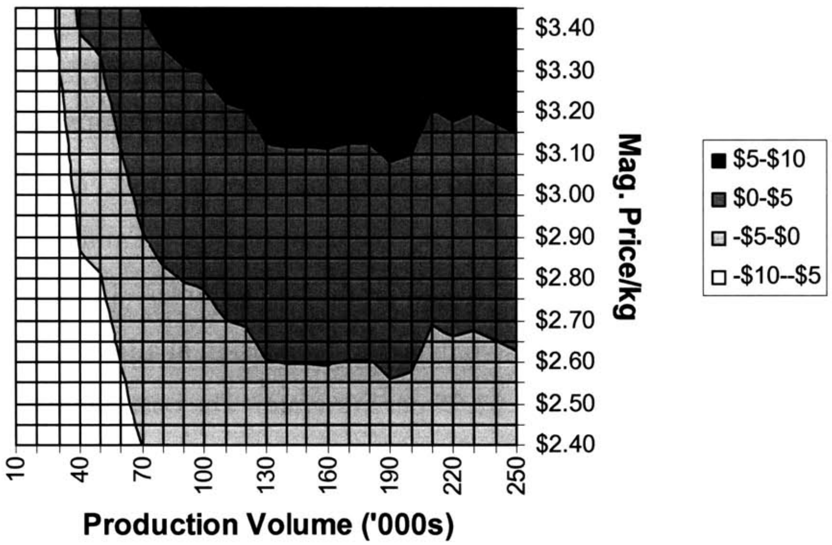

Figure 4-11. Mass Savings Value Sensitivity to Magnesium Price and Production Volume – Shared

The cost of a third variant for both the steel and magnesium IP beams was also modeled to determine the effects of additional variants on the two designs relative costs. This variant was modeled as being 10% shorter than variant one. As with the previous case, the steel variants shared brackets and some structure, while the magnesium designs shared only brackets and had unique die cast structures. Figure 4-12 shows the standalone, shared, and incremental costs for the two designs. The shortening of the IP beams caused a marked reduction in the material cost for the magnesium design. While the standalone cost of the first magnesium variant was 5% lower than that of its steel counterpart, the standalone cost for the third magnesium variant is 15% lower than that of the steel design. The incremental cost of the third steel variant was 47% less than its standalone cost; this figure was similar to the 49% incremental cost differential for the second steel variant. The incremental cost for the third magnesium variant was 17% lower than its standalone cost, similar to the 19% incremental cost savings for the second magnesium variant. Figure 4-13 shows the shared and standalone costs for all three variants. The total shared costs for the three steel variants were 33% lower than their standalone costs; this was higher than the 25% cost savings for the two steel IP beams. For the three magnesium variants, the total cost savings from sharing were 13%; this was higher than the 10% savings for the two magnesium variants. The total costs for the three steel magnesium variants were 22% higher than those of the steel variants (compared with 18% for the case of two variants). The additional variant increased the cost advantage of the steel IP beam design.

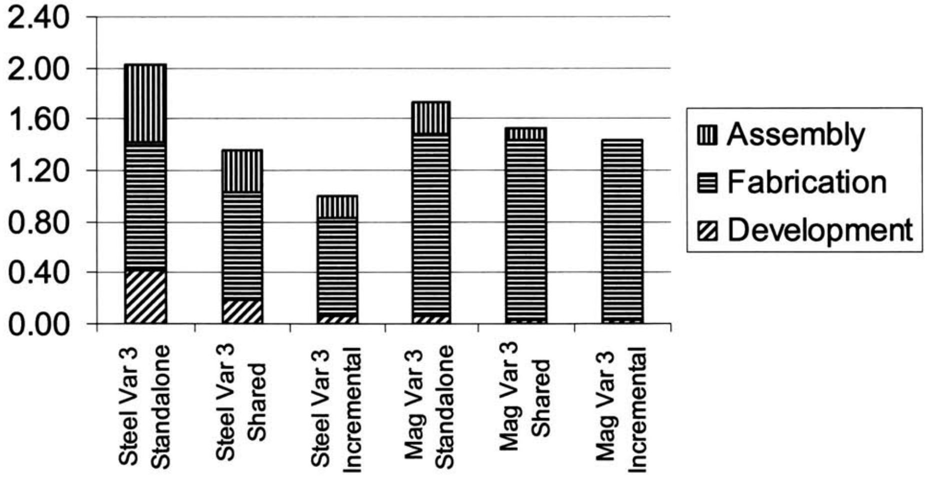

Figure 4-12. Total Costs for Third Variant

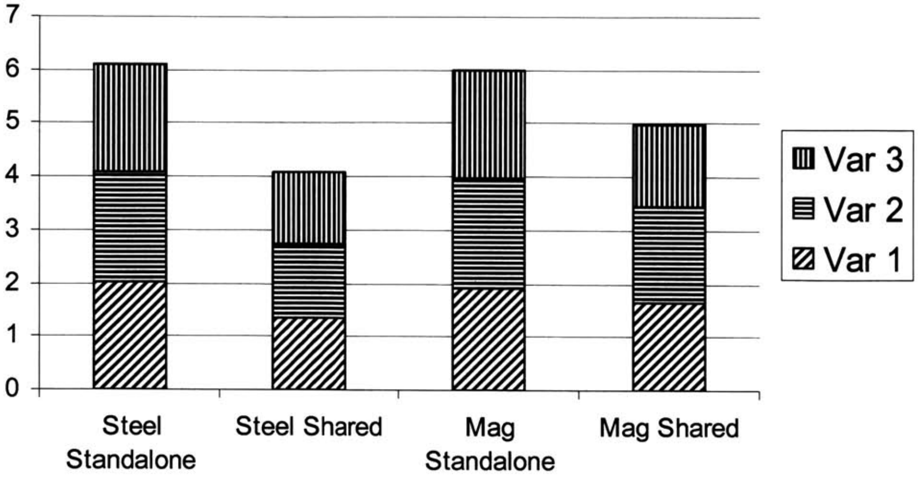

Figure 4-13. Standalone and Shared Costs for IP Beam Variants

5. Insights and Future Work

Insights from the analyses and future work are described in this chapter. Section 5.1 discusses inferences derived from the design of the various engineer surveys and the collection of data. Section 5.2 details insights gleaned from the results presented in the preceding case studies. Finally, opportunities for extension and new directions for this work are described in Section 5.5.

5.1 Development Model Insights

To determine the cost drivers of automotive product development and create a process-based cost model for the development process required a large amount of data to be gathered. This data came from several departments, organizational levels, and dozens of individuals. Meisl suggests that an interviewer should aim to create a good relationship with the respondent; the interviewer should be knowledgeable, objective, non-controversial, and flexible [83]. These suggestions were found to be very useful. It was very important to know the proper terminology and job functions when interviewing the engineers of the various groups. This ensured that responses to consistent questions were being given. The ability to be objective and non-controversial was also found to be very important. Engineers were understandably uneasy about giving data regarding the time it took them to perform tasks. It was very important to reassure them that this data was being collected along with data from several other engineers, and was not going to be used to assess individual or group performance. It was also crucial to inform the interviewee that while accurate data was desired exact answers were not expected. The use of examples or references (preferably visual) was also found to be useful when asking engineers to make subjective rankings or estimations (i.e. complexity estimation). This better enabled engineers to assign a subjective measure to the part or assembly in question.

There were three categories of data gathered for the formulation of the development model. The first type of information involved individual engineers working on individual parts. This category included data from both design and formability engineers. These engineers worked on a wide range of parts; not surprisingly, these parts required dramatically different amounts of engineering effort. In some cases, this range of effort spanned four orders of magnitude. Furthermore, since these engineers to not keep detailed records of design time by part, data in this category tended to be quantized (usually in multiples of four or eight). Correlations of data from these two development stages also had lower R^2 (multiple regression correlation coefficients). The second category of data consisted of a single engineer or very small group of engineers and technicians working on prescribed sets of tasks. This included both the computer aided and physical validation stages of the development process. In contrast to the design and formability stages, there was very little variability in the engineering effort required for these stages. This was most likely due to the standardized nature of this work. The final category of data included complex tasks that were performed by large groups of people. This encompassed the fabrication and assembly engineering stages of the development process. Correlations of data from these two development stages had higher R^2's than the data collected from individual engineers. Correlations for the engineering effort required for tooling design of stamping dies had an extremely high R^2. Since this data is used for accounting purposes, it is extremely well tracked. Better documentation of engineering effort required for the design and formability stages would most likely lead to better correlations and higher fidelity models.

Some overall inferences were drawn from the results of the statistical analyses of the collected and the results from the cases studies. First of all, contrary to expectations, the number of years of experience for an engineer did not play a statistically significant role in determination of engineering effort required for the development stages involving individual engineers. Experience did have a negative correlation with engineering effort, but it was not statistically significant. Secondly, labor costs accounted for the vast majority of total development cost. In the case of the entry-level steel unibody vehicle, labor cost accounted for almost 80% of total development cost. Overhead, computer software and hardware, and physical prototypes made up the balance. The engineering required for the fabrication and assembly stages of the development process accounted for the vast majority of costs. In most cases these two categories accounted for over 80% of total development cost. The reduction of labor costs and the reduction of assembly and fabrication engineering costs from the sharing of parts are two ways by which to substantially lower total development costs.

5.2 Overall Cost Estimation Insights

Overall there were several inferences gleaned from the cases studies analyzed in this work. Fabrication of constituent parts accounted for the majority of costs in all cases. Assembly costs accounted for the second largest portion of costs, while development cost accounted for the smallest portion. Cost savings from shared parts, for the variant combinations studied, varied greatly. In all cases, reduced assembly costs accounted for a large portion of total cost savings. In most cases, development costs, while a small portion of total costs, accounted for a large portion of the cost savings. Fabrication cost savings were generally limited to reduced tooling costs from the sharing of parts. Savings from reduced fabrication costs were limited by three factors. One, in most cases, the parts with the highest tooling costs were variant specific. Two, the assumption of full utilization for fabrication equipment, and three, a high portion of variable (mostly material) costs also limited the opportunity for reduced fabrication costs from part sharing. Considering the IP beam case, the consolidation of parts within the magnesium design limited the opportunity for cost savings from sharing. Parts consolidation markedly reduced development and assembly costs as a portion of total costs. Since these two cost categories dominated cost savings due to sharing, the magnesium IP beam had limited cost savings opportunities. The magnesium IP beams also had large variant specific parts that required unique tooling and a large portion of material costs. In an analogous manner, the large portion of materials cost and reduced tooling required for the tubular steel bodies-in-white also reduced the opportunities for cost savings in that case.

The importance of strategic assumptions, such as product lifetime and annual production volume were found to be very important in determining which product family strategy performed better. For the two body-in-white structures, the steel unibody retained higher cost savings at higher production volumes and longer product lifetimes. Conversely, the tubular structure had higher cost savings at very low product lifetimes and production volumes. In the case of the magnesium and steel IP beam comparison, magnesium prices, as well as production volume and product life, played a large role in determining which design performed better. The range over which magnesium was preferable to steel was drastically reduced when sharing was included.

5.3 Sharing Metric Comparison

The amount of sharing, as measured by the various metrics, varied greatly both between metrics and between product family cases. The two magnesium IP beam variants had the highest piece count sharing, but very low sharing as measured by the other metrics. The steel IP beams had very high sharing by all measures. Figure 5-1 shows the relationship between the value of the sharing metric and the amount of cost savings from sharing, for the eight variant pairs studied in this work. Some cases had a high measure of piece count sharing, but this did not result in a high level cost savings. The same was true for both the mass and piece cost weighted metrics. The fabrication investment weighted sharing metric was shown to be a better predictor of cost savings than the other metrics. Table 5-1 shows the R^2 values for correlations between sharing metrics and cost savings. The fabrication investment weighted metric has a much higher R^2 than all the other sharing metrics. This was not an intuitive result given that most of the cost savings from sharing resulted from reduced assembly and in most cases development costs, not part fabrication. Given that process-based fabrication cost models are available, investments could be used to screen non-variant specific parts that would be good candidates for sharing.

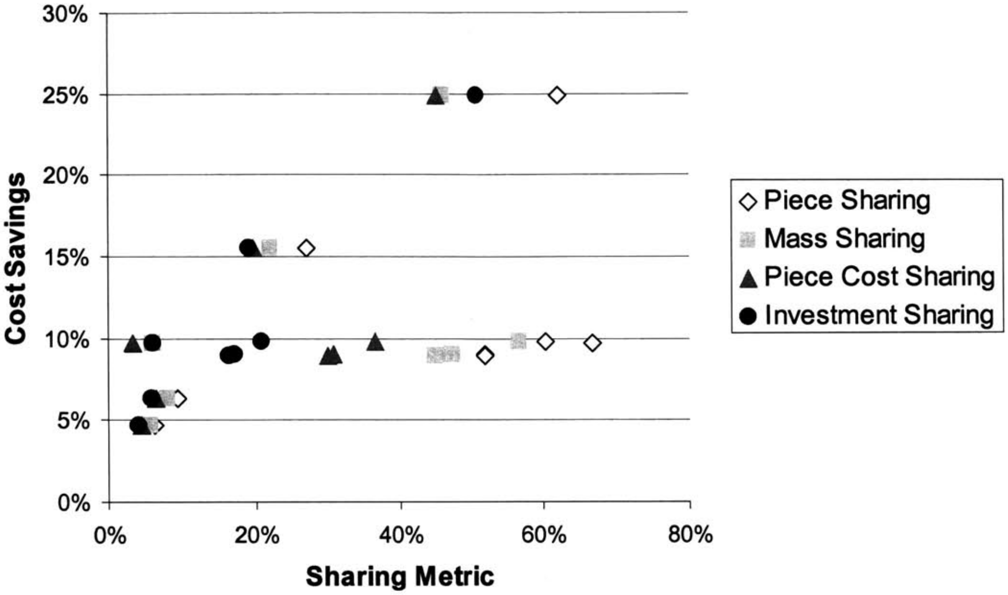

Figure 5-1. Cost Savings vs. Amount of Sharing for Various Metrics

Table 5-1. Performance of Sharing Metrics in Predicting Cost Savings

Method	R^2
Piece Sharing	0.08
Mass Sharing	0.02
Piece Cost Sharing	0.33
Fabrication Investment Sharing	0.84

5.4 Limitations

While several useful insights were derived from this work, some limitations should be noted. Variable costs such as labor, materials, and energy were assumed to be unaffected by sharing. No bulk purchasing or collective bargaining was taken into account. It is possible that these effects could result in better performance for product families with higher portions of variable costs. Standalone designs were assumed to have identical bills of material as those of their shared counterparts. The over engineering of certain parts to facilitate sharing was not considered. Consideration of over engineering could cause standalone variants to be less expensive, and thus reduce the amount of cost savings from the sharing of parts. Some minimum cost savings hurdle rate should be used to ensure that part sharing is worthwhile.

5.5 Future Work

While the results presented are believed to be adaptable to other areas, future work should examine additional processes and products. The work presented here was limited to automotive subassemblies and consisted mostly of metal forming processes. Future work could model the development, fabrication, and assembly of other product categories such as electronics or consume products. This would require more fabrication processes and assembly methods to be modeled. Less capital-intensive industries and those that use high value materials would be of particular interest.

The ability to estimate both total incremental investment and lead times allows for a real options approach to product development to be implemented. Given the high level of variability in marketing forecasts, as mentioned by Jordan and Graves [39], the value of staged verses simultaneous rollout could be evaluated. A binominal tree, representing alternative states of the world, could be used with outputs from the model, volatility estimations, and an estimated rate of return. This approach would allow decision makers to examine whether to launch products all at once, or to pursue a staged rollout strategy. This could be useful when a new make or styling change is proposed. This approach would allow for alternative architectures to be analyzed as a result of various outcomes (high acceptance/high volume/additional models; low acceptance/low volume/short product lifetime).

As mentioned previously, and demonstrated within the case studies, one way in which product differentiation can be achieved is through the use of product platforms. Another way in which product differentiation can be achieved is through flexible (CNC-like) manufacturing. Modeling the cost of development, fabrication, and assembly for flexible manufacturing would allow for a comparison to be made between these two methods of achieving product differentiation. It is hypothesized that production volume, number of variants, and product lifetime would greatly affect strategy preference.

While this work focused on the use of part sharing to reduce costs, part sharing could also be used to increase recycling and reuse. The sharing of parts and use of common materials could make reclamation of some materials economically feasible. Part sharing and materials selection for a product family could be used to formulate desired inputs for recycled materials. The cost differential between a "recycling enhanced" and a baseline case could be used along with the costs/benefits of recycling to determine a suitable strategy.

During the collection of data about the engineering effort required to make part changes, a dependence on the original design was often mentioned. The design software allowed for the full parameterization of designs. For instance, all features of a part could be linked to one or two overriding characteristics (i.e. length or width). This full parameterization did not usually take place due to deadlines and the additional work that it required. A study of how long full parameterization of designs would take, as compared to the faster solution could provide useful insights. If designs were changed often, would the total effort for the fully parameterized option actually be lower? The downstream effects of being able to easily update detailed designs could also be analyzed.

6. Conclusions

The goal of this work was to address issues concerning the effects of early product development decisions. Process-based cost models for development, fabrication, and assembly were used to explicitly present the trade-offs between different manufacturing and architecture strategies. Several ordinal metrics were used to assess alternative product family architectures. These metrics were related to cost savings of a particular product family and compared to a group of standalone products. Several conclusions, which had been previously stated qualitatively or anecdotally, were quantified using the process-based cost models developed for this work. Specifically:

- The process-based cost model of the product development process was used to quantify and identify the major cost drivers of both the various development stages as well as the overall development process. For the design, formability, and fabrication engineering stages of the development process, part size and complexity were found to be the major drivers of engineering effort, and thus cost. The number of parts, subassembly complexity, and the number of equivalent spot welds were found to be the main drivers of assembly engineering effort. Computer aided and physical validation effort was found to be fairly uniform and standardized. The assembly and fabrication engineering stages of the development process accounted for the majority of total development cost (usually over 80%). Labor costs represented the vast majority of total development cost (approximately 80%), with overhead, computer software and hardware, and physical prototype making up the balance.
- Fabrication costs accounted for the majority of total development project cost. Assembly costs also made up a large portion, while development costs accounted for the small balance. Materials and tooling were usually the largest portions of total fabrication cost; while overhead and tooling were usually the largest portions of assembly cost.
- In the case of the magnesium IP beam, parts consolidation was found to reduce both development cost and development process cycle time. Parts consolidation was also found to reduce tooling cost and assembly cost. The combination of

reduced development cost and assembly cost, made the magnesium design more competitive than results that a fabrication cost evaluation would have led to. This quantified the widely held belief that parts consolidation can reduce costs.

- The sharing of parts was found to reduce costs compared to the standalone costs of a product family. While this was an expected result, this work allowed these savings to be quantified and related to the various product family assessment metrics. The amount of cost savings was dependent on the amount of sharing, the portion of variable costs, the annual production volume, and the product lifetime. Increased variable costs were usually found to decrease the effects of part sharing on cost savings. Decreased production volume increased the effects of part sharing on cost savings; shorter product lifetimes also increased the effects of part sharing on cost savings.

In addition to the quantification of expected results, several unexpected conclusions were derived from the results. Specifically:

- While the data available did not evenly represent the entire range of experience, an engineer's experience was not found to be statistically significantly correlated with reduced engineering effort for a given task.
- While fabrication accounted for the majority of the cost for a development project, reduced assembly costs, from shared assembly operations, usually accounted for the majority of cost savings. In most cases reduced development costs, from shard parts, also made up a large portion (i.e. larger than fabrication cost savings) of total cost savings.
- Parts consolidation was found to be less cost competitive when the cost saving effects of sharing were included, than on a standalone basis. While the integration of parts reduced the opportunities for sharing across product variants, parts consolidation was found to reduce the cost saving effects of sharing by reducing assembly and development cost, and by increasing fabrication (mostly variable) cost. Since assembly and development cost accounted for the vast majority of savings from parts sharing, parts consolidation mitigated the effects of the parts sharing.

- Ordinal metrics were used to assess the amount of sharing for each of the product families examined. There were a wide range of metric values for the various product families analyzed. There were also a wide range of values for the alternative sharing metrics for a given product family. Linear regression analysis was used to show that both the piece count and mass weighted metrics (similar to those used in industry) have little or no relationship to cost savings. By contrast, the fabrication investment weighted metric had a much higher correlation with cost savings than any of the other metrics. This final conclusion should provide useful insight when developing product platforms. In particular, given access to either process-based cost models of fabrication or to accounting data of sufficiently similar parts, it should be possible for those designers to readily identify those components which would be the most valuable to share. Ranking parts according to fabrication investment should allow for a more targeted and effective component sharing strategy.

7. Appendices

7.1 Engineer Surveys

7.1.1 Designer Survey

Name: ______________________________________

E-Mail: ______________________________________

Phone: ______________________________________

Years of Design Experience: _____

Part 1

Part Name _____________________________

Type of Part (stamping, casting, etc.)

____

Part Complexity simple bracket -1 vs. floorpan -5; number of features)

____

Part Length ______________________m

Part Width ______________________m

Part Height ______________________m

Is Part Structural _________ (yes or no)

Tube Time Required to Complete Part ____________________________ hrs.

Calendar Time Required to Complete Part _________________________ days

Percent of above tube time required to make scale change to part (lengthen or widen)

______ %

Percent of above tube time required to add one average feature to part

______ %

Number of Iterations in Part Design_____________

Amount of Project Overlap ____________ (1 – all task done in parallel; 5 – all tasks done sequentially)

Likelihood of Having to Change Part ___________ (1 – not likely; 3-very likely)

Sensitivity to Changes in Other Parts ___________ (1 – not sensitive; 3-very sensitive)

Probability of Change Needed in Design __________ %

7.1.2 Formability Engineer Survey

Name: ______________________

E-Mail: _______________________________

Phone: ______________

Years of Experience: _____

Part 1

Part Name _________________________________

Manufacturing Technology _______________ (stamping, casting, etc)

Material ________________ (steel, aluminum)

Novelty of Technology _______ (1-stamping; 5-composites)

Part Complexity _________ (1 -bracket; 5 - floor pan)

Part Length _____________________m

Part Width _____________________m

Part Height _____________________m

Is Part on the Surface _________ (yes or no)

Total Time Spent doing formability of this part _______ (hrs.)

Number of Formability Analyses Done _________________

Amount of CPU time per analysis________________ (hrs.)

Calendar Time Required for Formability ________ weeks

7.1.3 CAE Engineer Survey

Name: ________________________

E-Mail: ________________________

Phone: ________________________

Years of Experience: _____

Analysis 1

Project ____________________________

Test Description

____

____

Number of Engineers/Technicians __________

Manufacturing Technology (stamping, casting, etc)________________

Material (steel, aluminum)_______________

Part/Assembly Complexity_______________(1-bracket/bracket assm. 5-floorpan/motor compartment)

Material and Process Complexity _____________ (1-stamped steel bracket; 5 – filled composite bodyside)

Material and Process Novelty____________________ (1-stamped steel; 5 – filled composite)

Structural Part _________ (yes;no) – Physical Tests

Time Required to set up analysis ___________ hrs.

Time Required to run analysis _____________hrs.

CPU Time ____________hrs.

Calendar Time Required set-up and analysis _________ weeks

7.1.4 Validation Engineer Survey

Name: ____________________

E-Mail: ______________________

Phone: _____________________

Years of Experience: _____

Validation Project 1

Name ____

Property (parts/assembly) Needed

Test Description

____

____

Manufacturing Technology (stamping, casting, etc)_______________

Material (steel, aluminum)______________

Part/Assembly Complexity______________(1-bracket/bracket assm. 5-floorpan/motor compartment)

Material and Process Complexity ____________ (1-stamped steel bracket; 5 – filled composite bodyside)

Material and Process Novelty___________________ (1-stamped steel; 5 – filled composite)

Number of Engineers/Technicians _________

Time Required to Run Test ____________hrs.

Calendar Time Required for Testing ________ weeks

Could this test be shared across variant products from platform____________

7.1.5 Fabrication Engineer Survey

Name: ___________________________________

E-Mail: ___________________________________

Phone: ___________________________________

Years of Experience: _____

Part 1

Part Name ________________________________

Manufacturing Technology ______________ (stamping, casting, etc)

Material _______________ (steel, aluminum)

Novelty of Technology _______ (1-stamping; 5-composites)

Part Complexity _________ (1 -bracket; 5 - floor pan)

Part Length ____________________m

Part Width ____________________m

Part Height ____________________m

Total Time Spent Developing this Process _______ (hrs.) (determining required equipment size, process flow, other expensed activites)

Total Time Spent Designing Tooling_______ (hrs.)

7.1.6 Assembly Engineer Survey

Name: ______________________________

E-Mail: ______________________________

Phone: ______________________________

Assembly 1

Assembly Name ____________________________

Number of Parts _______

Assembly Complexity ________ (1-Bracket Assembly; 5-Motor Compartment)

Amount of Joining _______ equivalent spot welds

Number of Joining Methods ___________

Total Amount of Time Required to Engineer This Process (design tooling, work out sequence) ______hrs

Calendar Time Required for Assembly Development __________weeks

Percent of Original Time Required to Engineer Assembly of Slight Variant (Longer Parts, Additional Parts)

_________ %

7.2 Statistical Results

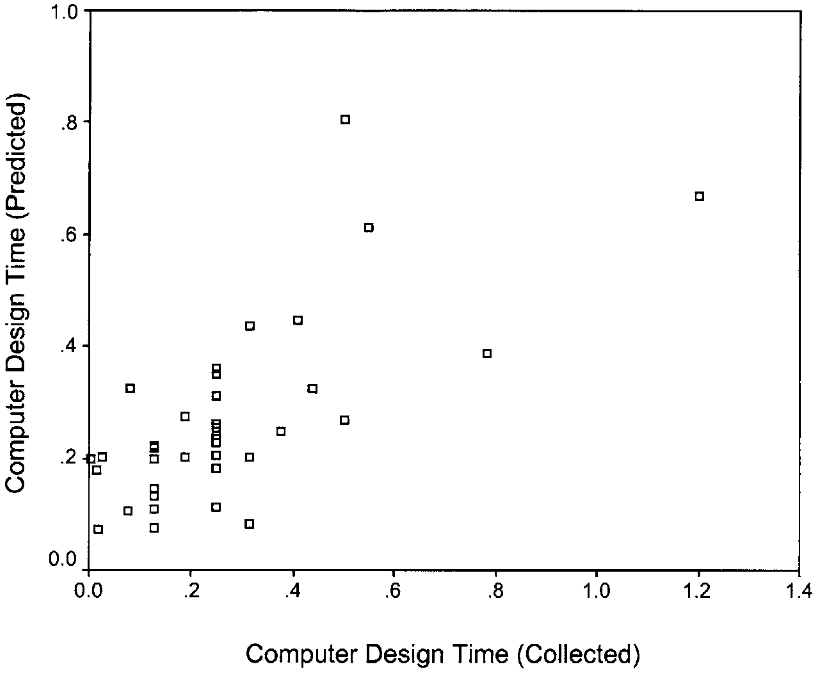

Figure 7-1. Predicted and Collected Data for Computer Design Time

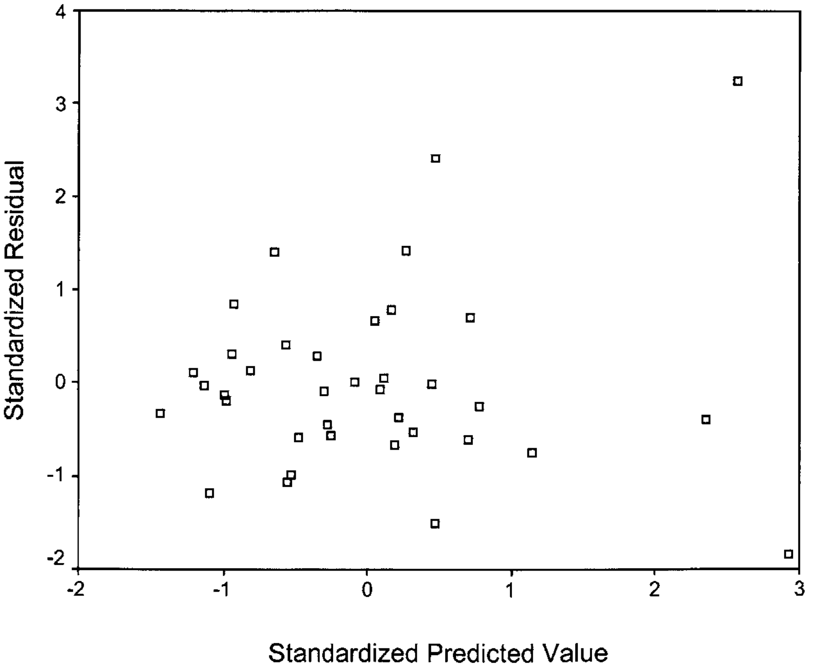

Figure 7-2. Standardized Residuals vs. Standardized Predicted Values for Computer Design Time

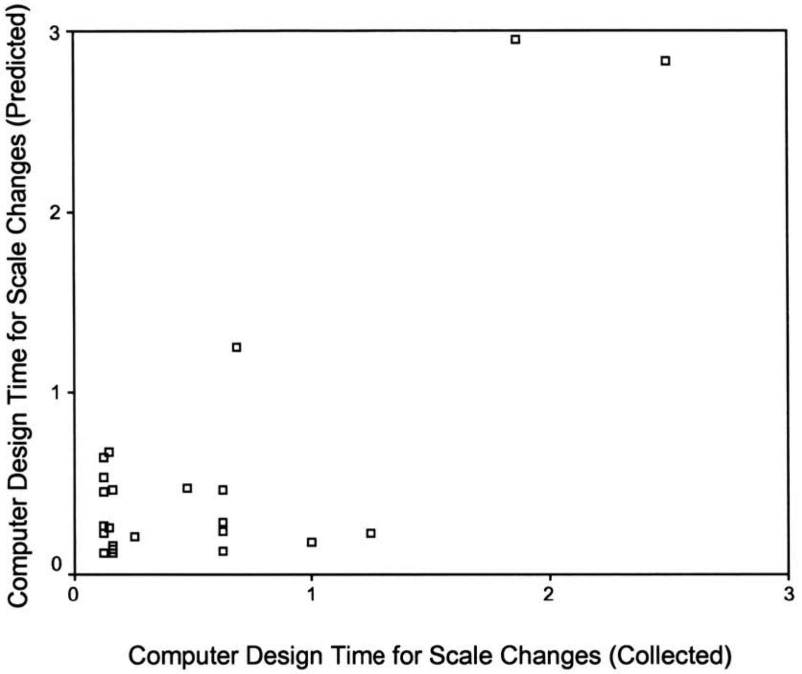

Figure 7-3. Predicted and Collected Data for Computer Design Time for Scale Changes

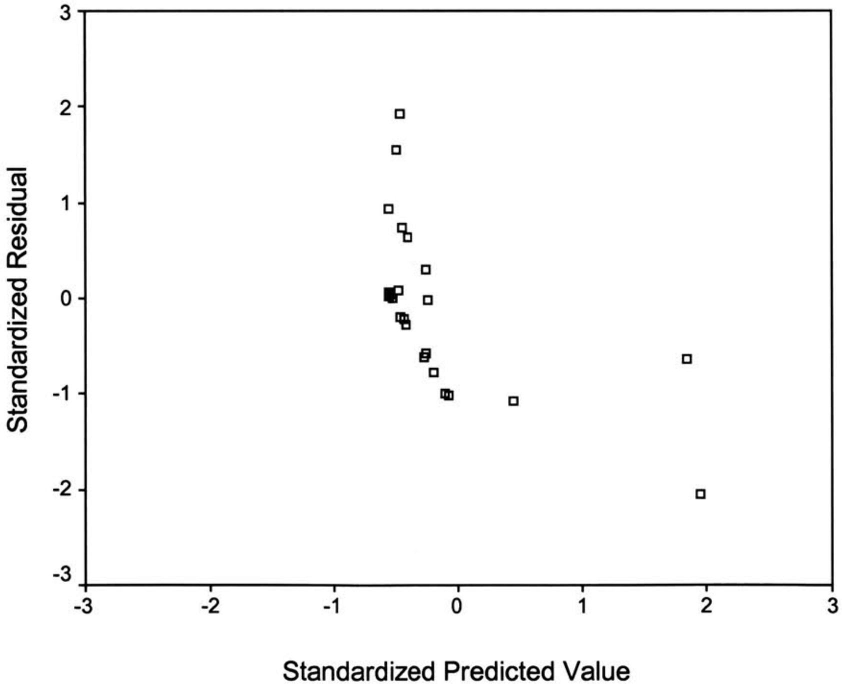

Figure 7-4. Standardized Residuals vs. Standardized Predicted Values for Computer Design Time for Scale Changes

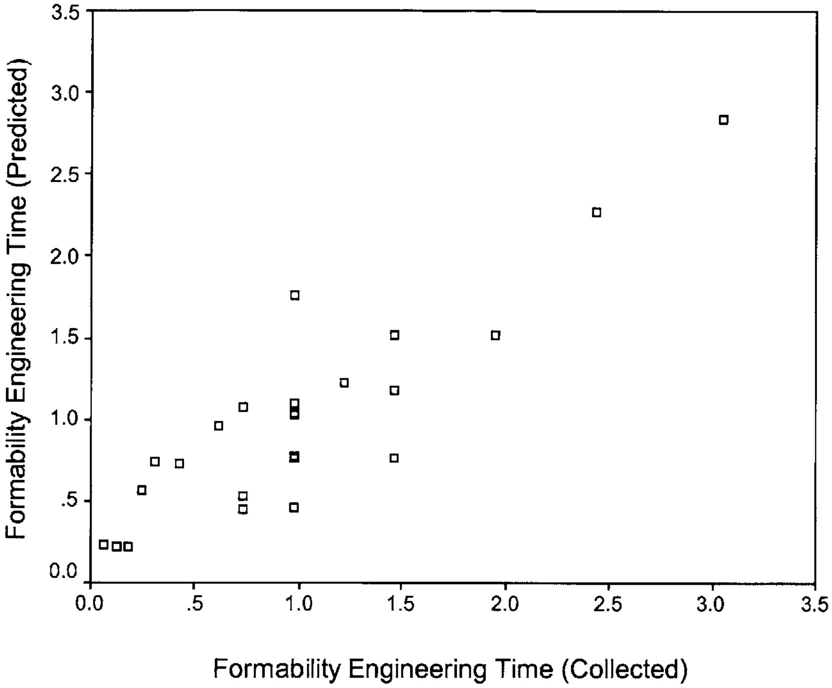

Figure 7-5. Predicted and Collected Data for Formability Engineering Time

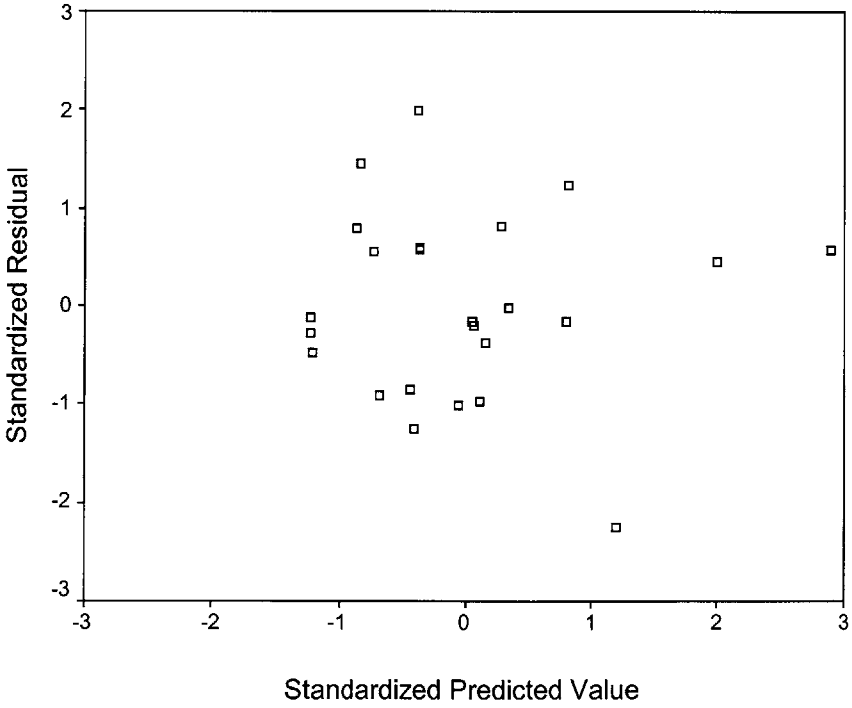

Figure 7-6. Standardized Residuals vs. Standardized Predicted Values for Formability Engineering Time

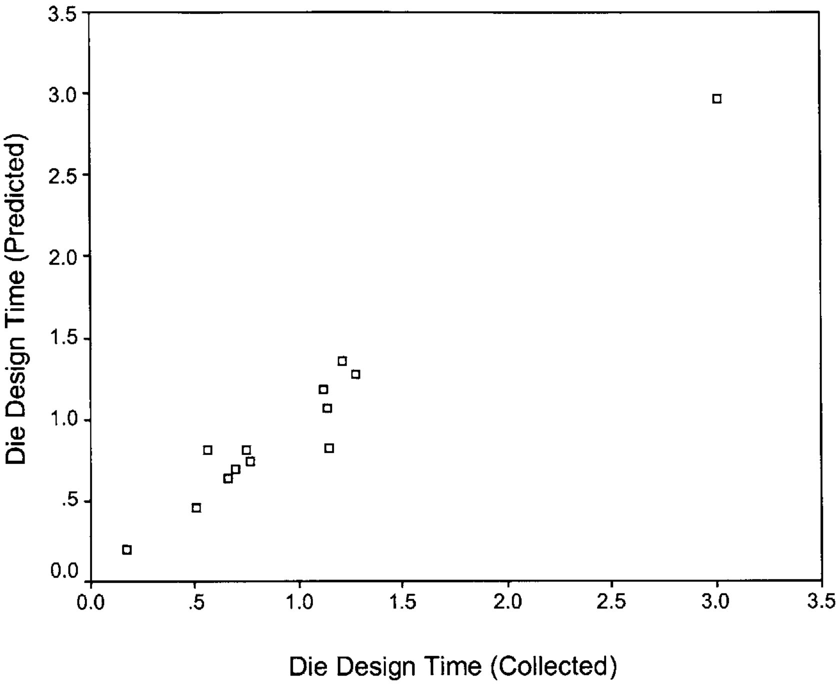

Figure 7-7. Predicted and Collected Data for Die Design Time

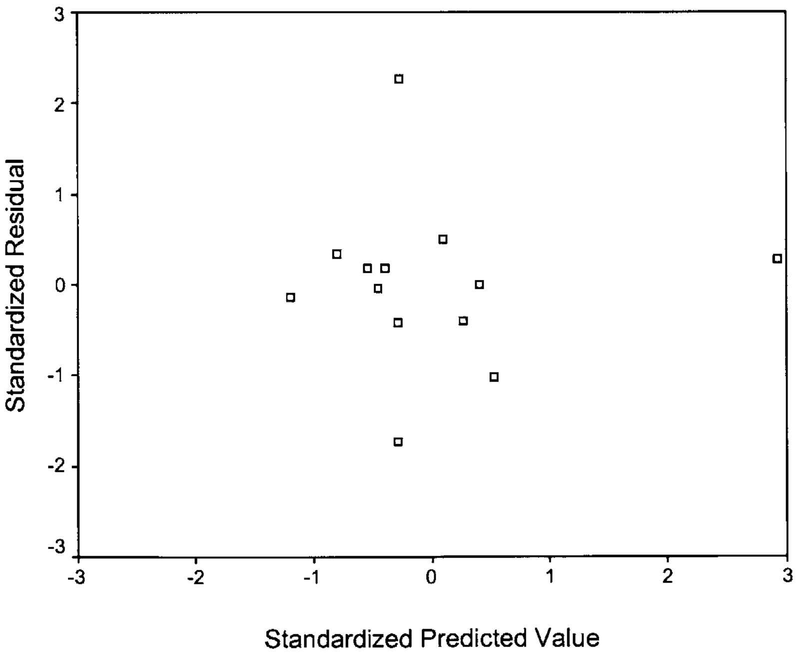

Figure 7-8. Standardized Residuals vs. Standardized Predicted Values for Die Design Time

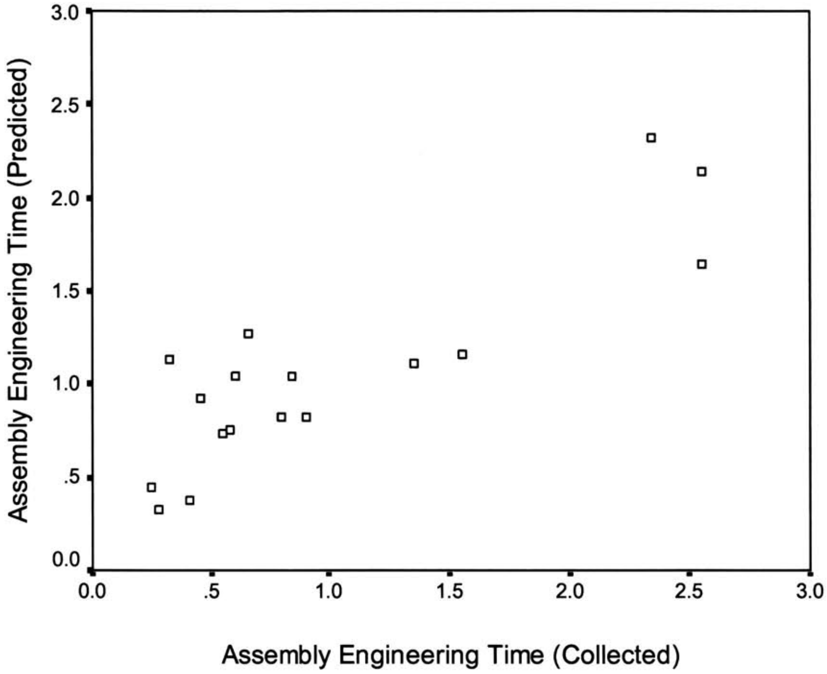

Figure 7-9. Predicted and Collected Data for Assembly Engineering Time

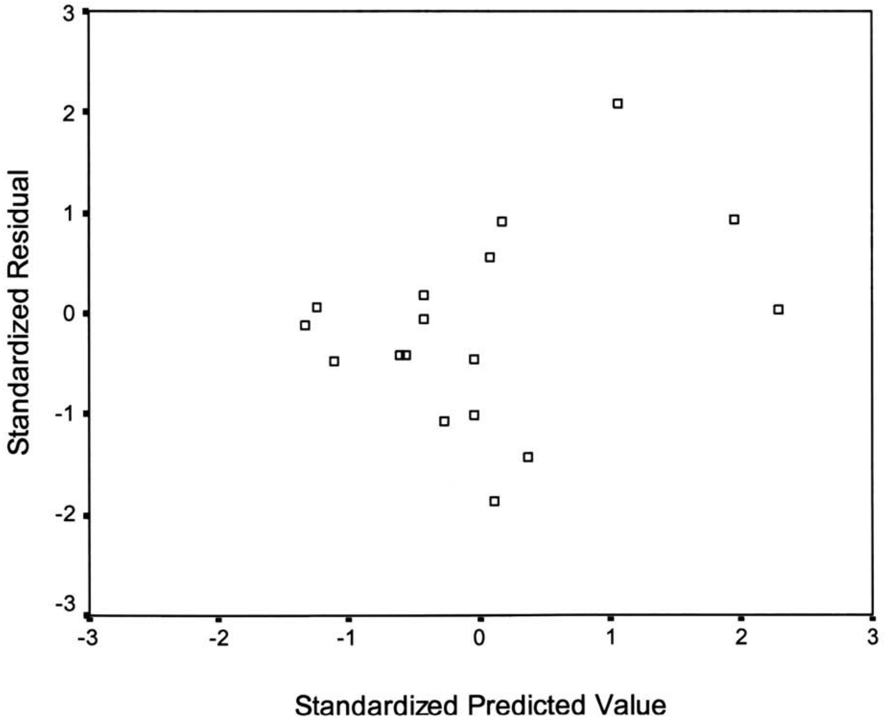

Figure 7-10. Standardized Residuals vs. Standardized Predicted Values for Assembly Engineering Time

7.3 Part Sharing for Different Architectures – Supplemental Data

7.3.1 Traditional Stamped Steel Body

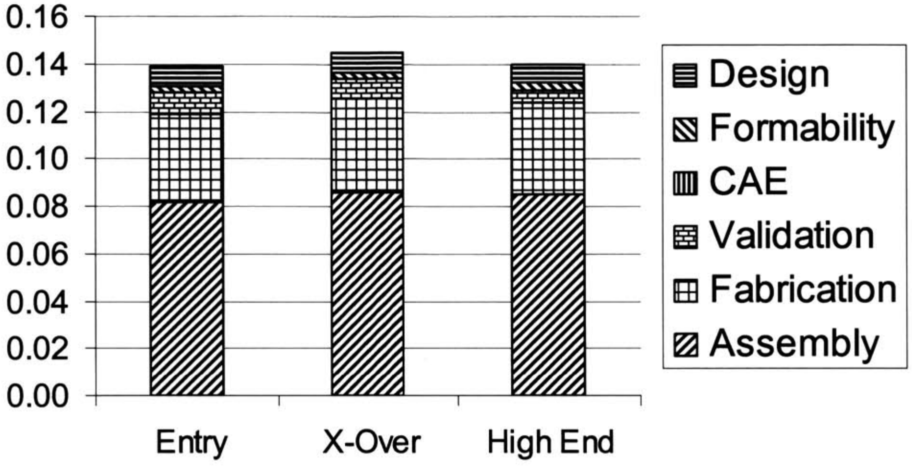

Figure 7-11. Standalone Development Costs for Steel Unibodies

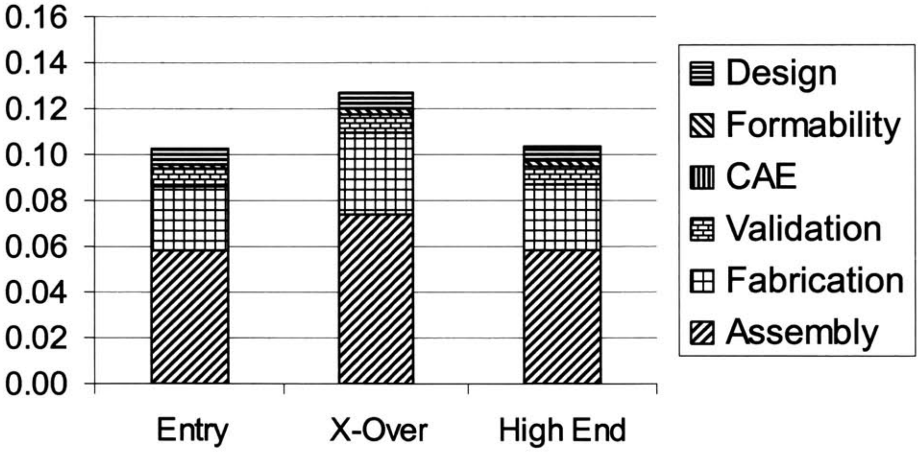

Figure 7-12. Shared Development Costs for Steel Unibodies

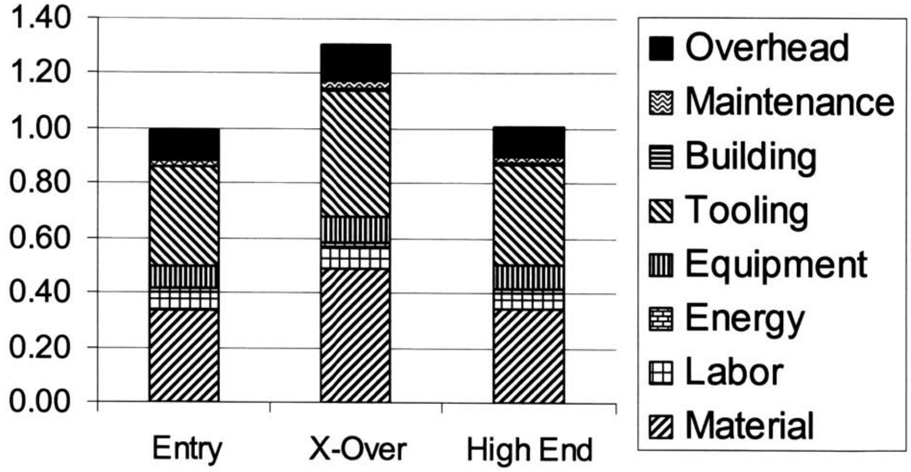

Figure 7-13. Standalone Fabrication Costs for Steel Unibodies

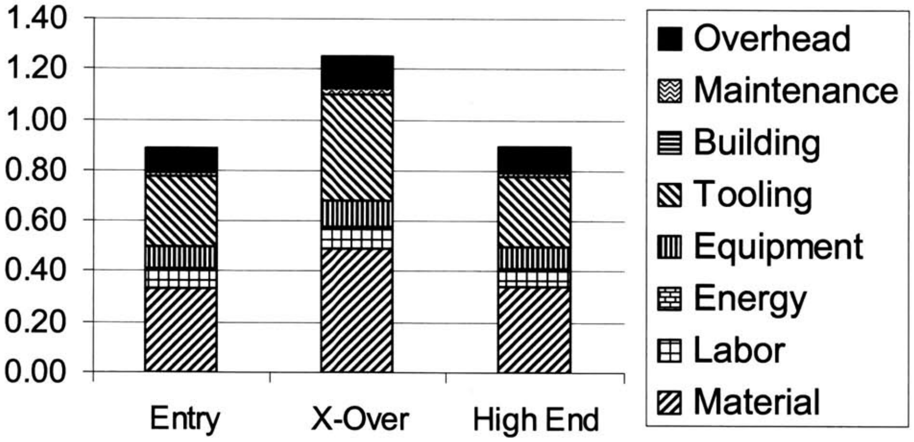

Figure 7-14. Shared Fabrication Costs for Steel Unibodies

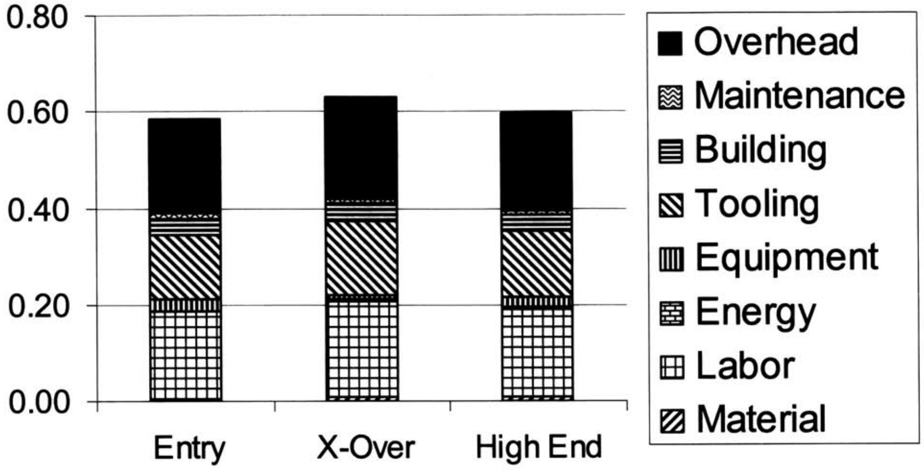

Figure 7-15. Standalone Assembly Costs for Steel Unibodies

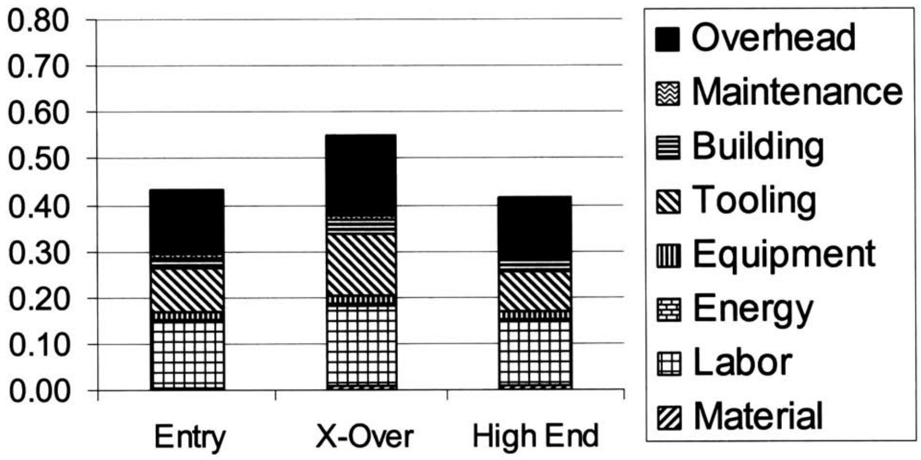

Figure 7-16. Shared Assembly Costs for Steel Unibodies

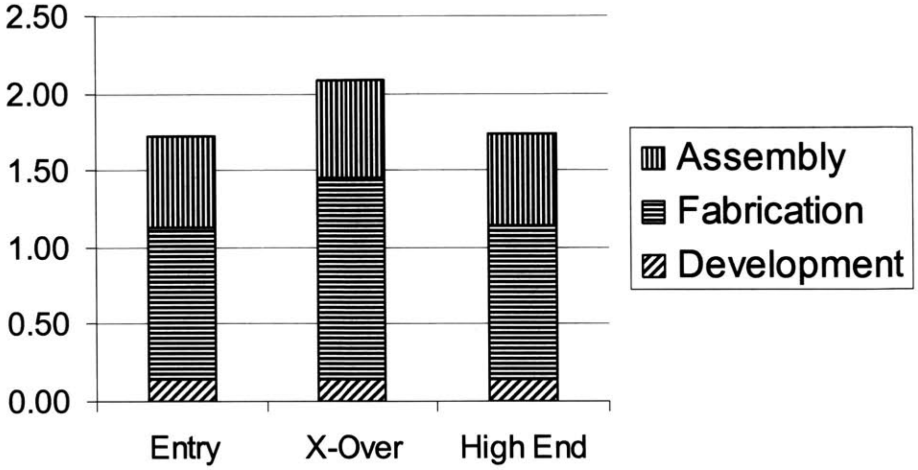

Figure 7-17. Standalone Total Costs for Steel Unibodies

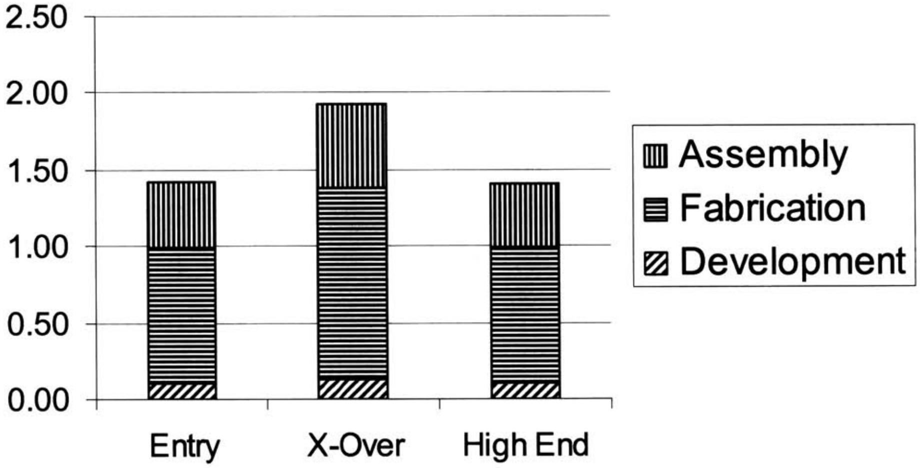

Figure 7-18. Shared Total Costs for Steel Unibodies

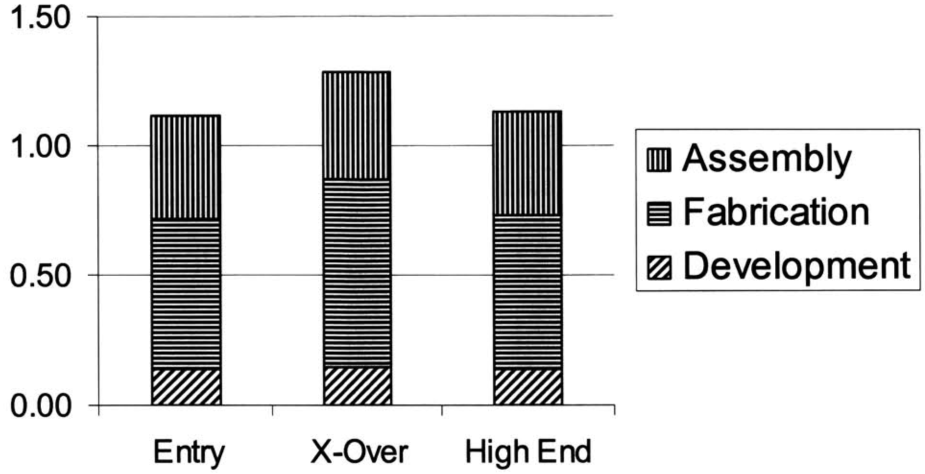

Figure 7-19. Standalone Total Fixed Costs for Steel Unibodies

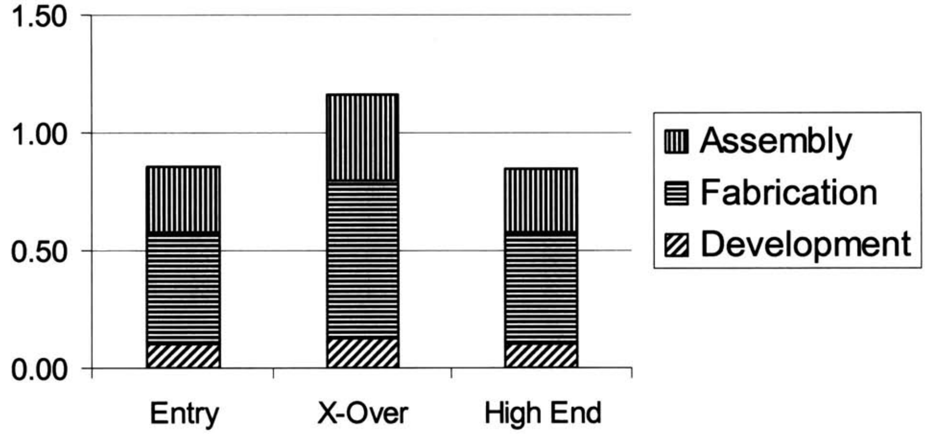

Figure 7-20. Shared Total Fixed Costs for Steel Unibodies

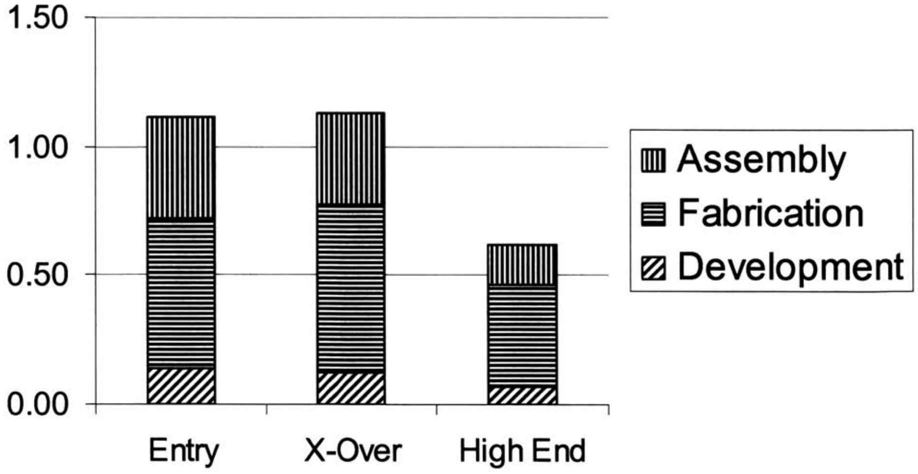

Figure 7-21. Incremental Total Fixed Costs for Steel Unibodies

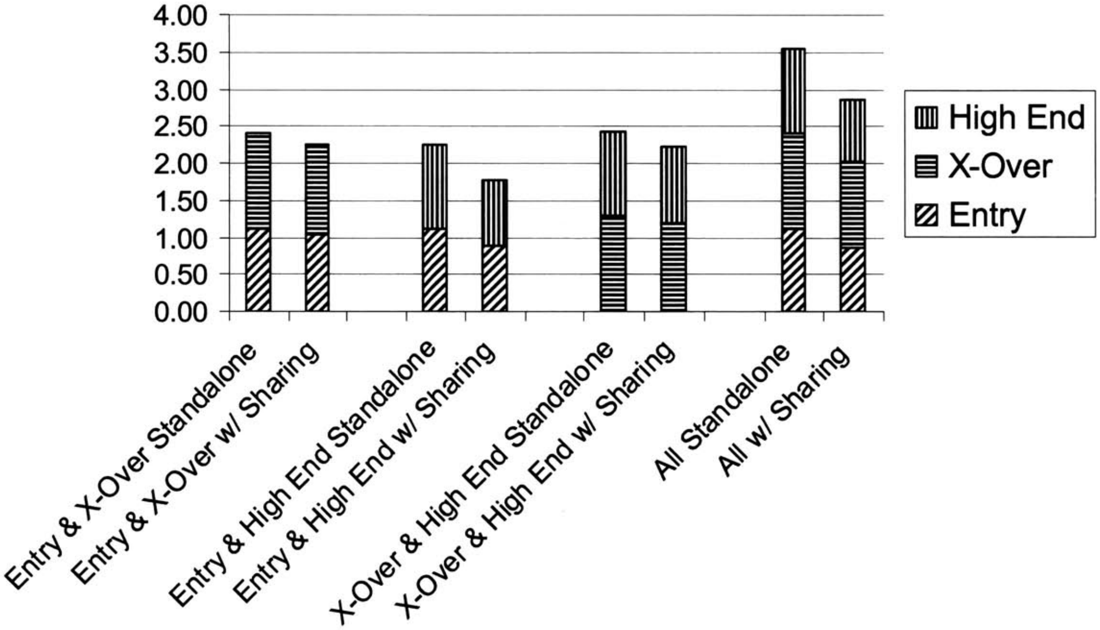

Figure 7-22. Steel Unibody Vehicle Fixed Costs - With and Without Sharing

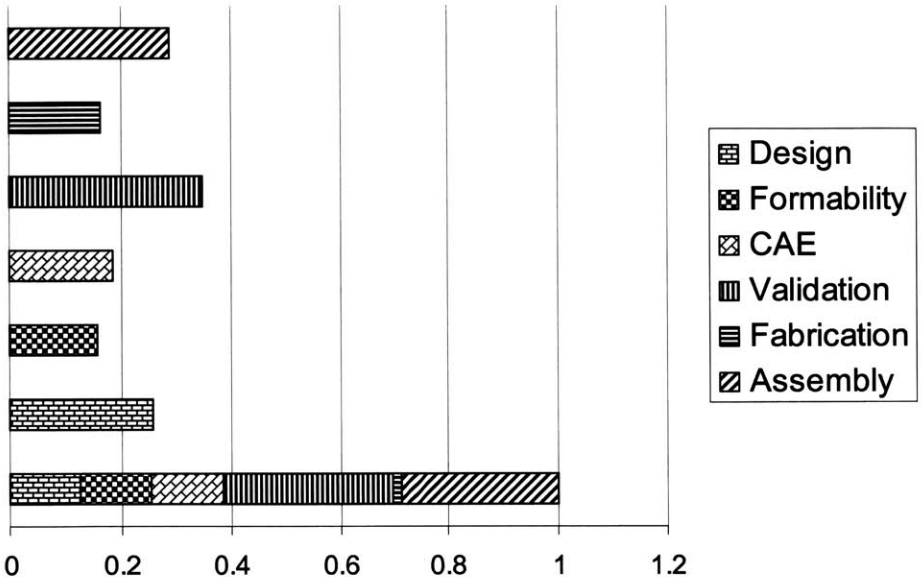

Figure 7-23. Standalone Development Time for Entry Model

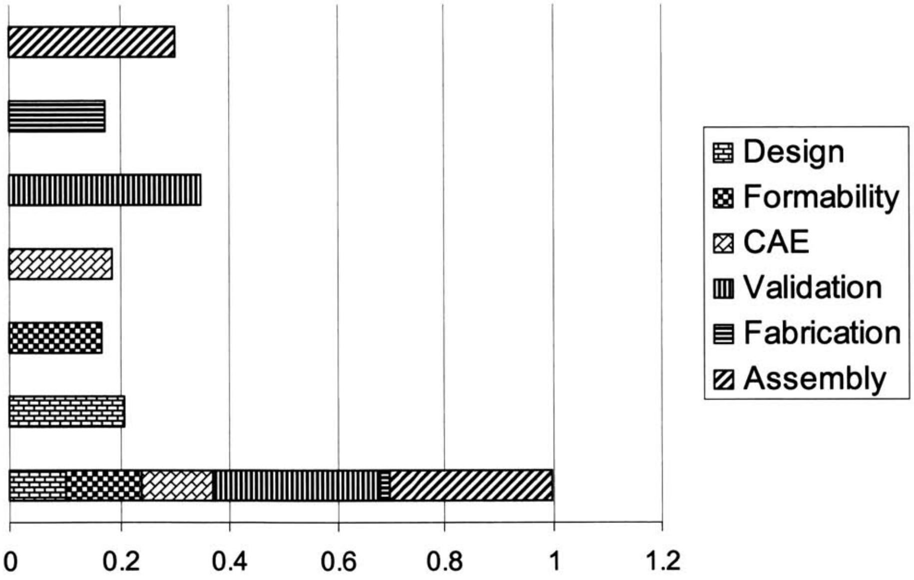

Figure 7-24. Standalone Development Time for Crossover Vehicle

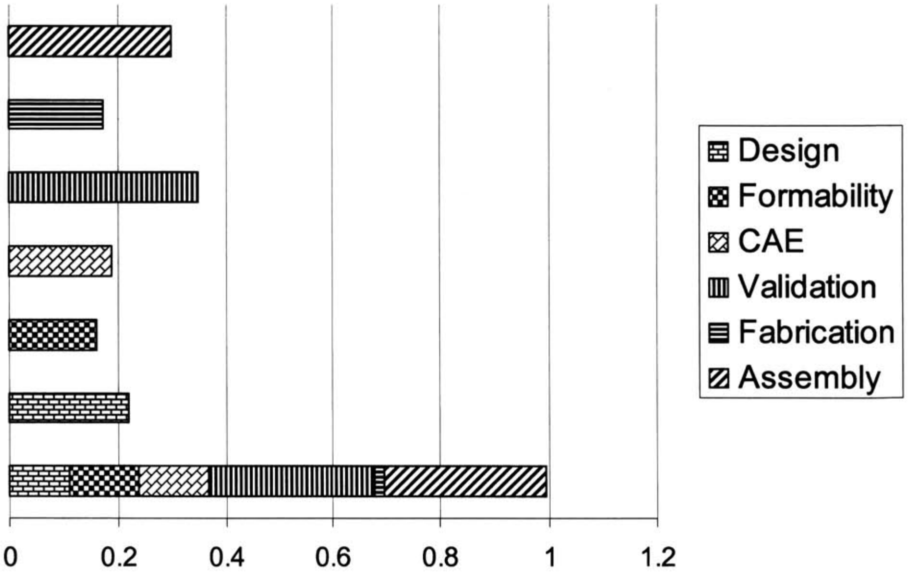

Figure 7-25. Standalone Development Time for High End Model

Table 7-1. Shared Development Costs for Steel Unibody (Normalized)

Shared - Development													
	Entry- Only	X-Over - Only	High End - Only	Entry& X-Over		Entry& High End		X-Over & High End		All 3		
	Entry	X-Over	High End	Entry	X-Over	Entry	High End	X-Over	High End	Entry	X-Over	High End
Assembly	0.082	0.086	0.085	0.075	0.079	0.060	0.063	0.077	0.076	0.058	0.074	0.059
Fabrication	0.037	0.039	0.039	0.035	0.037	0.029	0.031	0.036	0.035	0.028	0.035	0.029
Validation	0.009	0.009	0.005	0.009	0.009	0.007	0.007	0.007	0.007	0.008	0.008	0.008
CAE	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Formability	0.003	0.003	0.003	0.002	0.003	0.002	0.002	0.002	0.002	0.002	0.002	0.002
Design	0.008	0.008	0.008	0.008	0.008	0.007	0.007	0.008	0.008	0.007	0.008	0.007
Total	**0.139**	**0.145**	**0.140**	**0.129**	**0.135**	**0.105**	**0.110**	**0.130**	**0.128**	**0.102**	**0.127**	**0.104**

Table 7-2. Incremental Development Costs for Steel Unibody (Normalized)

Incremental - Development													
	Entry- Only	X-Over - Only	High End - Only	Entry& X-Over		Entry& High End		X-Over & High End		All 3		
	Entry	X-Over	High End	Entry	X-Over	Entry	High End	X-Over	High End	Entry	X-Over	High End
Assembly	0.082	0.086	0.085	0.082	0.072	0.082	0.042	0.086	0.067	0.082	0.072	0.037
Fabrication	0.037	0.039	0.039	0.037	0.034	0.037	0.022	0.039	0.032	0.037	0.034	0.021
Validation	0.009	0.009	0.005	0.009	0.009	0.009	0.005	0.009	0.005	0.009	0.009	0.005
CAE	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Formability	0.003	0.003	0.003	0.003	0.002	0.003	0.001	0.003	0.002	0.003	0.002	0.001
Design	0.008	0.008	0.008	0.008	0.007	0.008	0.005	0.008	0.007	0.008	0.007	0.005
Total	**0.139**	**0.145**	**0.140**	**0.139**	**0.125**	**0.139**	**0.076**	**0.145**	**0.113**	**0.139**	**0.125**	**0.069**

Table 7-3. Shared Fabrication Costs for Steel Unibody (Normalized)

	Shared - Fabrication												
	Entry - Only	X-Over - Only	High End - Only	Entry & X-Over		Entry & High End		X-Over & High End		All 3		
	Entry	X-Over	High End	Entry	X-Over	Entry	High End	X-Over	High End	Entry	X-Over	High End
Material	0.33	0.49	0.34	0.33	0.49	0.33	0.34	0.49	0.34	0.33	0.49	0.34
Labor	0.07	0.08	0.06	0.07	0.08	0.07	0.06	0.08	0.06	0.07	0.08	0.06
Energy	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Equipment	0.08	0.10	0.09	0.08	0.10	0.08	0.09	0.10	0.09	0.08	0.10	0.09
Tooling	0.36	0.46	0.37	0.33	0.44	0.28	0.29	0.43	0.34	0.27	0.42	0.27
Building	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Maintenance	0.02	0.03	0.02	0.02	0.03	0.02	0.02	0.03	0.02	0.02	0.03	0.02
Overhead	0.11	0.13	0.11	0.11	0.13	0.10	0.10	0.13	0.10	0.10	0.13	0.10
Total	**0.99**	**1.30**	**1.00**	**0.96**	**1.27**	**0.90**	**0.91**	**1.26**	**0.96**	**0.89**	**1.25**	**0.89**

Table 7-4. Incremental Fabrication Costs for Steel Unibody (Normalized)

	Incremental - Fabrication												
	Entry - Only	X-Over - Only	High End - Only	Entry & X-Over		Entry & High End		X-Over & High End		All 3		
	Entry	X-Over	High End	Entry	X-Over	Entry	High End	X-Over	High End	Entry	X-Over	High End
Material	0.33	0.49	0.34	0.33	0.49	0.33	0.34	0.49	0.34	0.33	0.49	0.34
Labor	0.07	0.08	0.06	0.07	0.08	0.07	0.06	0.08	0.06	0.07	0.08	0.06
Energy	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Equipment	0.08	0.10	0.09	0.08	0.10	0.08	0.09	0.10	0.09	0.08	0.09	0.09
Tooling	0.36	0.46	0.37	0.36	0.41	0.36	0.22	0.46	0.30	0.36	0.40	0.21
Building	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Maintenance	0.02	0.03	0.02	0.02	0.03	0.02	0.02	0.03	0.02	0.02	0.02	0.01
Overhead	0.11	0.13	0.11	0.11	0.13	0.11	0.09	0.13	0.10	0.11	0.13	0.08
Total	**0.99**	**1.30**	**1.00**	**0.99**	**1.24**	**0.99**	**0.82**	**1.30**	**0.92**	**0.99**	**1.23**	**0.81**

Table 7-5. Shared Assembly Costs for Steel Unibody (Normalized)

Shared - Assembly												
	Entry - Only	X-Over - Only	High End - Only	Entry & X-Over		Entry & High End		X-Over & High End		All 3		
	Entry	X-Over	High End	Entry	X-Over	Entry	High End	X-Over	High End	Entry	X-Over	High End
Material	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Labor	0.18	0.20	0.19	0.16	0.18	0.14	0.15	0.18	0.17	0.14	0.17	0.14
Energy	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Equipment	0.02	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Tooling	0.13	0.15	0.14	0.12	0.14	0.10	0.09	0.14	0.12	0.09	0.13	0.09
Building	0.03	0.04	0.03	0.03	0.03	0.02	0.03	0.03	0.03	0.02	0.03	0.02
Maintenance	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Overhead	0.20	0.21	0.20	0.18	0.19	0.14	0.15	0.18	0.17	0.14	0.17	0.13
Total	**0.59**	**0.63**	**0.60**	**0.53**	**0.59**	**0.45**	**0.45**	**0.57**	**0.53**	**0.43**	**0.55**	**0.42**

Table 7-6. Incremental Assembly Costs for Steel Unibody (Normalized)

Incremental - Assembly												
	Entry - Only	X-Over - Only	High End - Only	Entry & X-Over		Entry & High End		X-Over & High End		All 3		
	Entry	X-Over	High End	Entry	X-Over	Entry	High End	X-Over	High End	Entry	X-Over	High End
Material	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Labor	0.18	0.20	0.19	0.18	0.17	0.18	0.11	0.20	0.14	0.18	0.17	0.11
Energy	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Equipment	0.02	0.01	0.02	0.02	0.02	0.02	0.02	0.01	0.03	0.02	0.02	0.02
Tooling	0.13	0.15	0.14	0.13	0.13	0.13	0.05	0.15	0.10	0.13	0.13	0.05
Building	0.03	0.04	0.03	0.03	0.03	0.03	0.02	0.04	0.03	0.03	0.03	0.02
Maintenance	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.01	0.01	0.01	0.01	0.00
Overhead	0.20	0.21	0.20	0.20	0.17	0.20	0.09	0.21	0.14	0.20	0.17	0.07
Total	**0.59**	**0.63**	**0.60**	**0.59**	**0.54**	**0.59**	**0.31**	**0.63**	**0.46**	**0.59**	**0.54**	**0.27**

7.3.2 Alternative Tubular Steel Structure

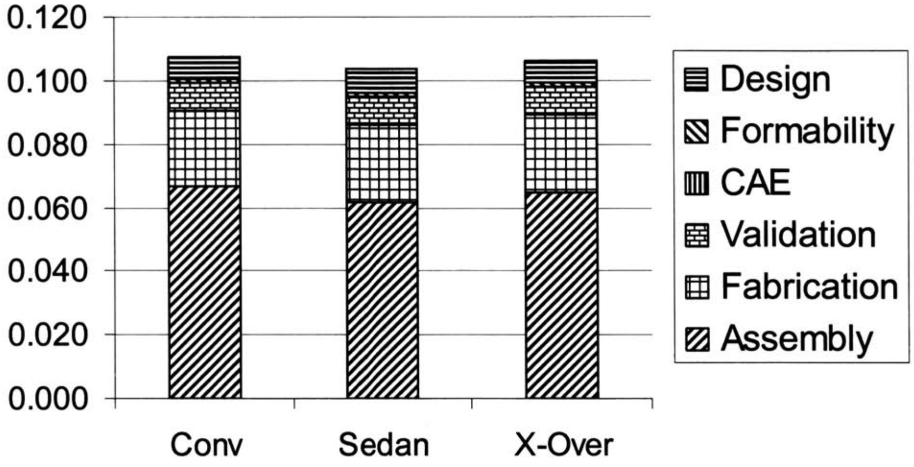

Figure 7-26. Standalone Development Costs for Tubular Steel Variants

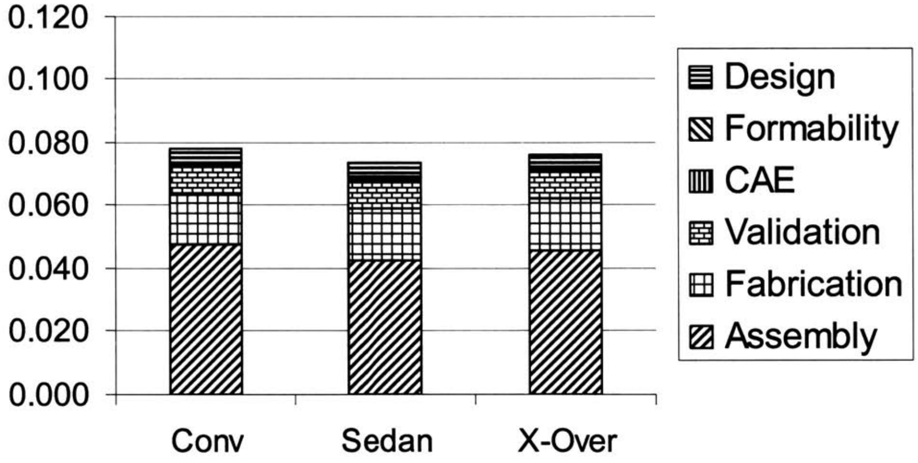

Figure 7-27. Shared Development Costs for Tubular Steel Variants

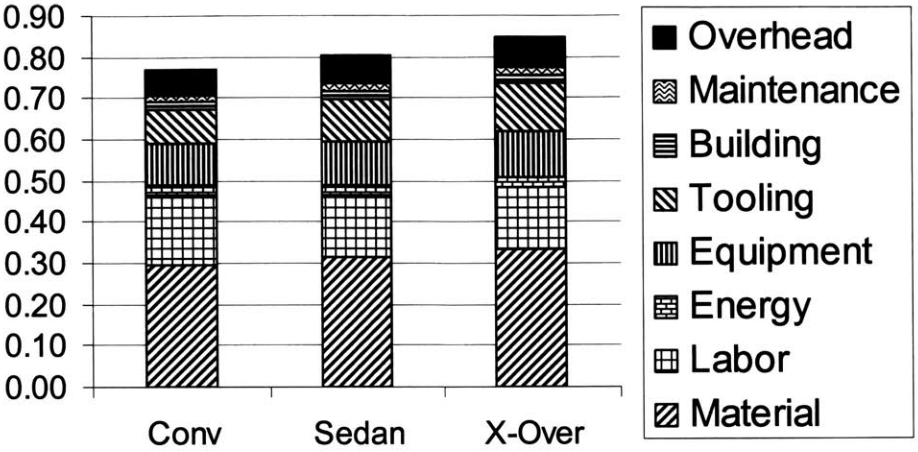

Figure 7-28. Standalone Fabrication Costs for Tubular Steel Variants

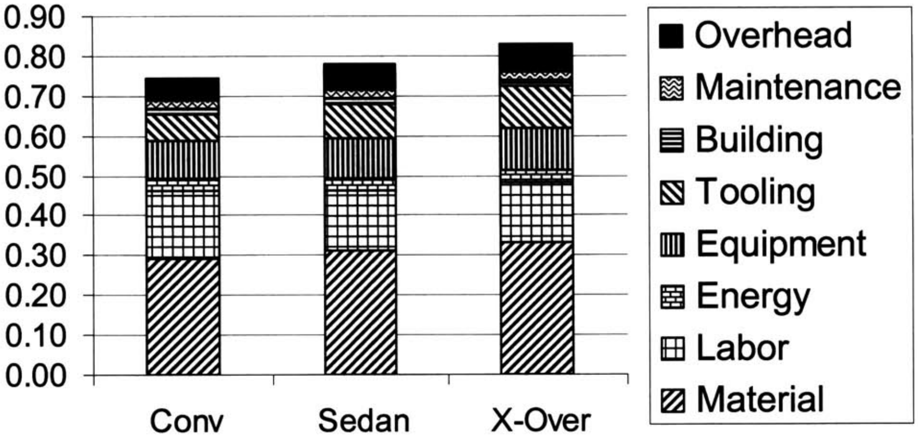

Figure 7-29. Shared Fabrication Costs for Tubular Steel Variants

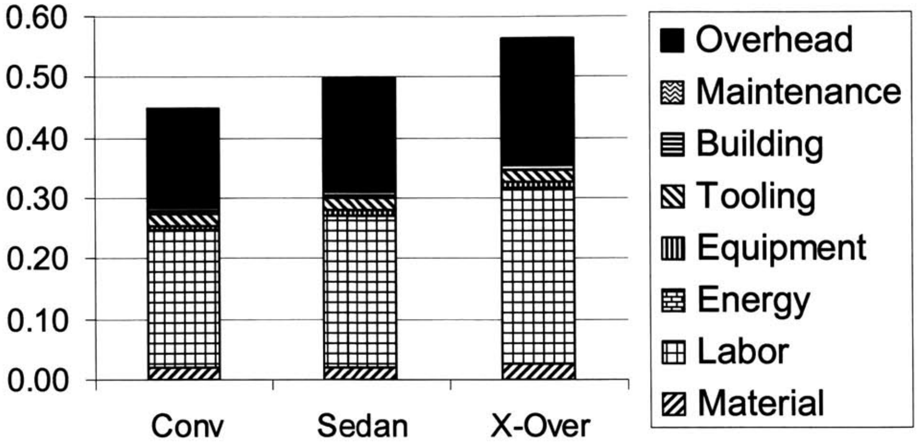

Figure 7-30. Standalone Assembly Costs for Tubular Steel Variants

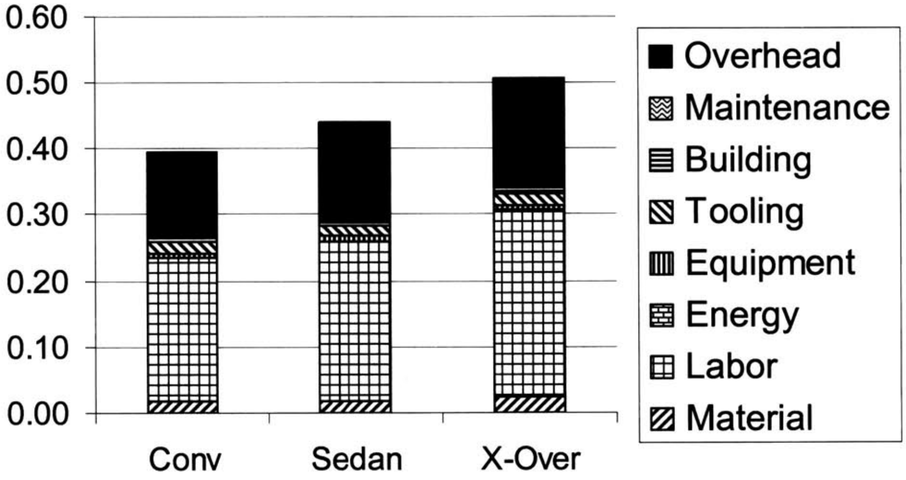

Figure 7-31. Shared Assembly Costs for Tubular Steel Variants

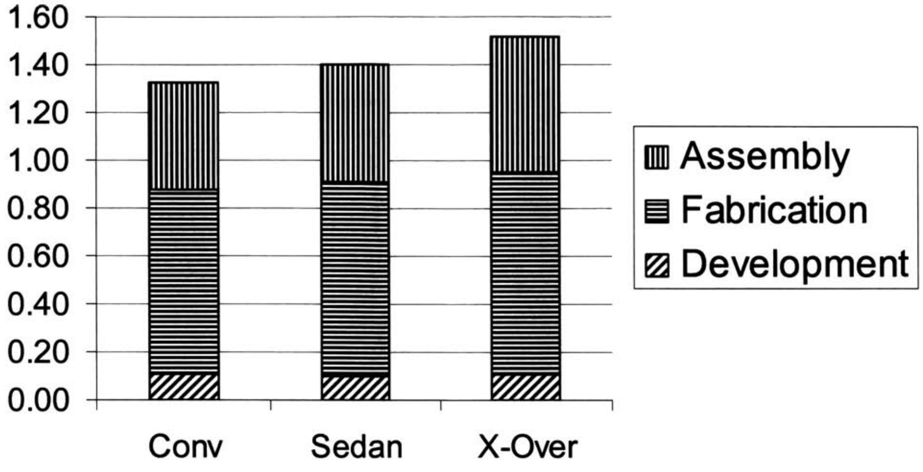

Figure 7-32. Standalone Total Costs for Tubular Steel Variants

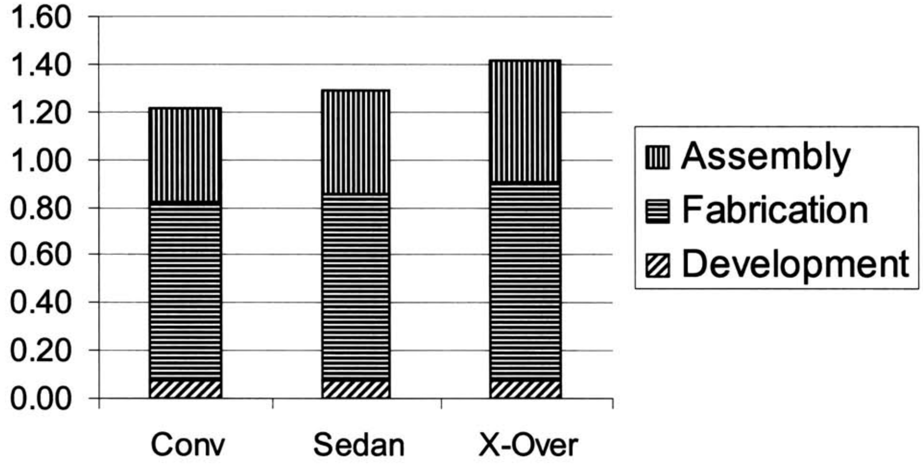

Figure 7-33. Shared Total Costs for Tubular Steel Variants

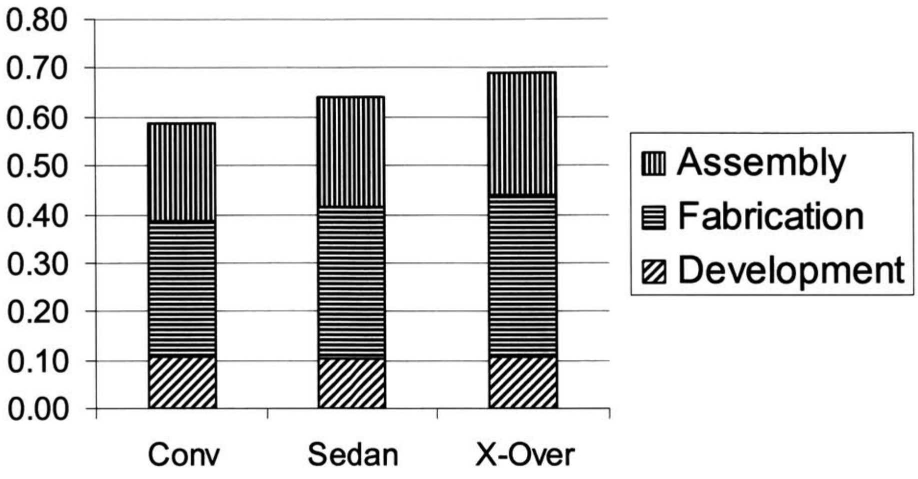

Figure 7-34. Standalone Total Fixed Costs for Tubular Steel Variants

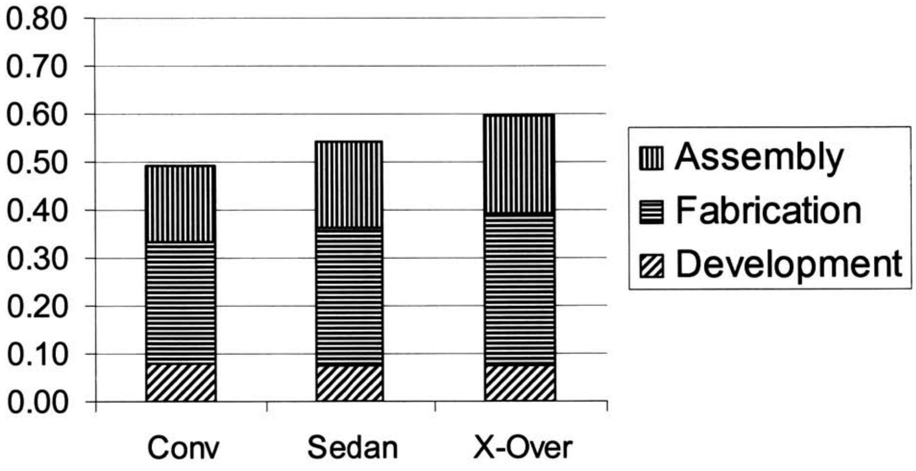

Figure 7-35. Shared Total Fixed Costs for Tubular Steel Variant Vehicles

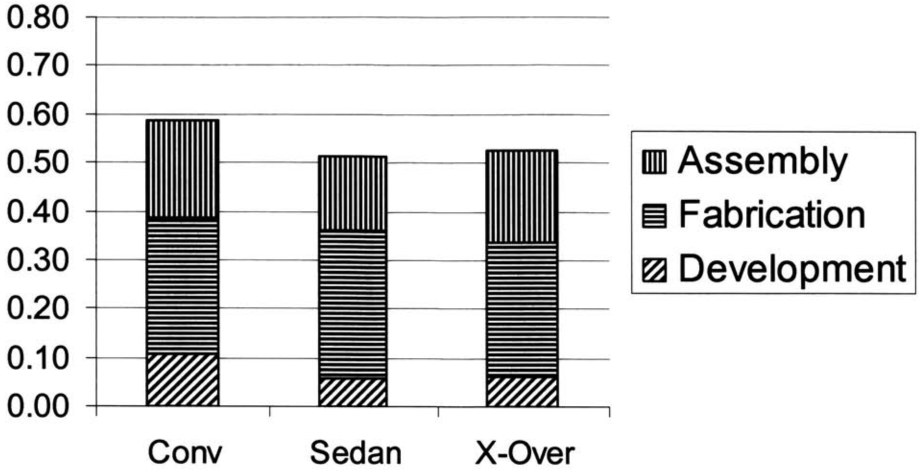

Figure 7-36. Incremental Total Fixed Costs for Tubular Steel Variants

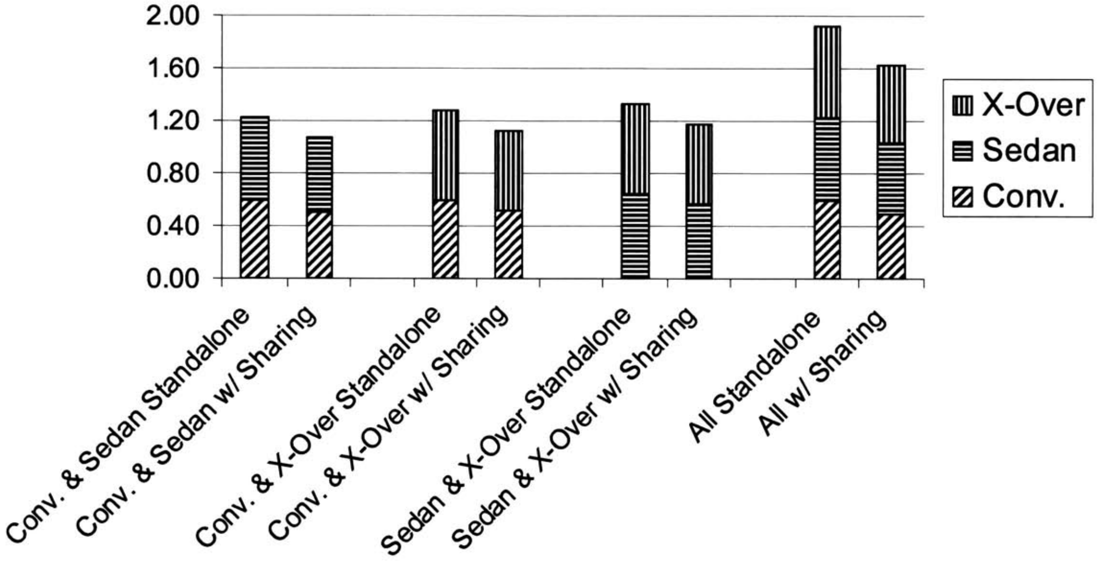

Figure 7-37. Tubular Steel Vehicle Fixed Costs - With and Without Sharing

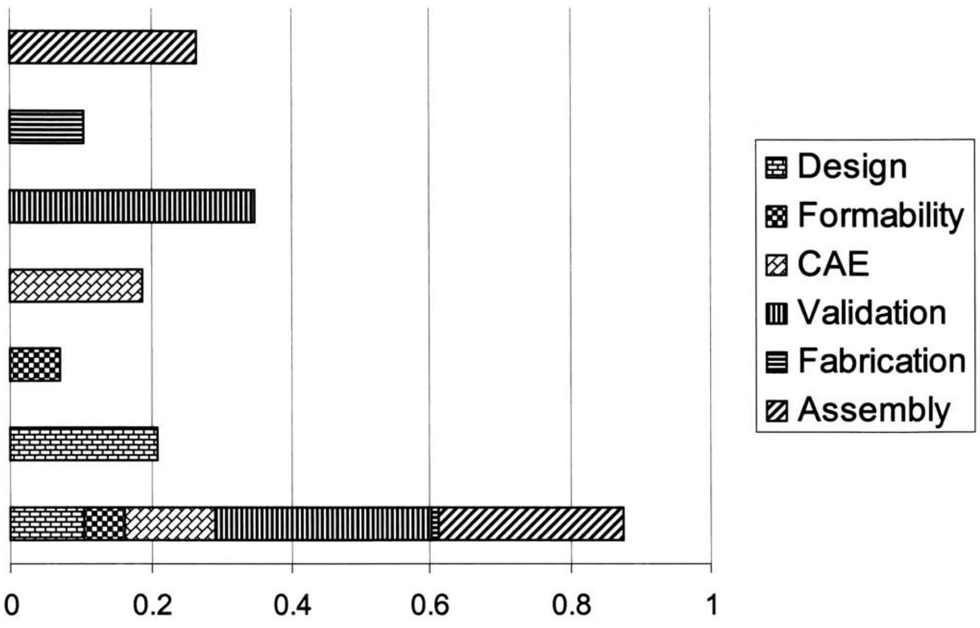

Figure 7-38. Standalone Development Time for Convertible

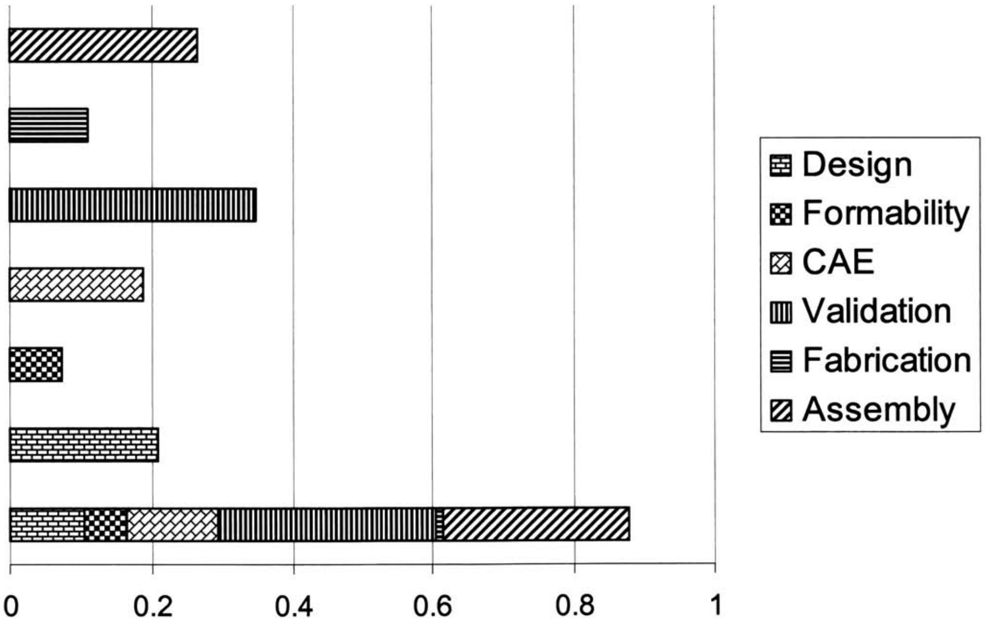

Figure 7-39. Standalone Development Time for Sedan

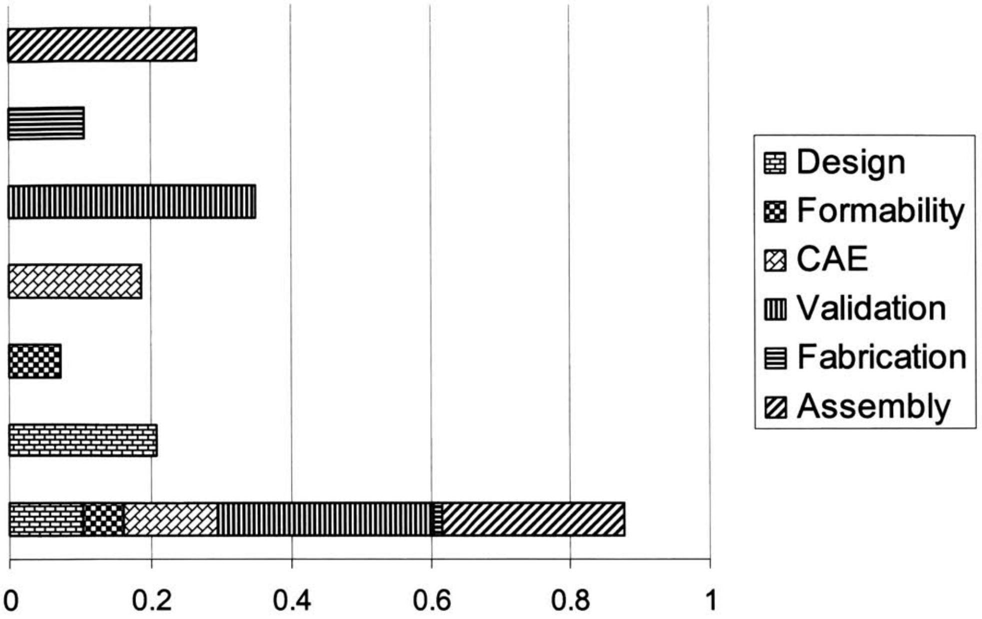

Figure 7-40. Standalone Development Time for Crossover

Table 7-7. Shared Development Costs for Tubular Steel Variants (Normalized)

Shared - Development													
	Conv - Only	Sedan - Only	X-Over - Only	Conv & Sed		Conv & X-Over		Sedan & X-Over		All 3		
	Conv	Sedan	X-Over	Conv	Sedan	Conv	X-Over	Sedan	X-Over	Conv	Sedan	X-Over
Assembly	0.067	0.062	0.065	0.052	0.047	0.052	0.050	0.047	0.050	0.048	0.043	0.046
Fabrication	0.024	0.024	0.025	0.018	0.019	0.018	0.019	0.019	0.019	0.016	0.017	0.017
Validation	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009
CAE	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Formability	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Design	0.007	0.007	0.007	0.005	0.005	0.006	0.005	0.006	0.005	0.005	0.005	0.004
Total	**0.11**	**0.10**	**0.11**	**0.09**	**0.08**	**0.09**	**0.08**	**0.08**	**0.08**	**0.08**	**0.07**	**0.08**

Table 7-8. Incremental Development Costs for Tubular Steel Variants (Normalized)

Incremental - Development													
	Conv - Only	Sedan - Only	X-Over - Only	Conv & Sed		Conv & X-Over		Sedan & X-Over		All 3		
	Conv	Sedan	X-Over	Conv	Sedan	Conv	X-Over	Sedan	X-Over	Conv	Sedan	X-Over
Assembly	0.067	0.062	0.065	0.067	0.033	0.067	0.036	0.062	0.036	0.067	0.033	0.036
Fabrication	0.024	0.024	0.025	0.024	0.013	0.024	0.013	0.024	0.013	0.024	0.013	0.013
Validation	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.009
CAE	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Formability	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Design	0.007	0.007	0.007	0.007	0.003	0.007	0.003	0.007	0.003	0.007	0.003	0.003
Total	**0.11**	**0.10**	**0.11**	**0.11**	**0.06**	**0.11**	**0.06**	**0.10**	**0.06**	**0.11**	**0.06**	**0.06**

Table 7-9. Shared Fabrication Costs for Tubular Steel Variants (Normalized)

Shared - Fabrication													
	Conv - Only	Sedan - Only	X-Over - Only	Conv & Sed		Conv & X-Over		Sedan & X-Over		All 3		
	Conv	Sedan	X-Over	Conv	Sedan	Conv	X-Over	Sedan	X-Over	Conv	Sedan	X-Over
Material	0.29	0.31	0.33	0.29	0.31	0.29	0.33	0.31	0.33	0.29	0.31	0.33
Labor	0.17	0.15	0.15	0.17	0.15	0.17	0.15	0.15	0.15	0.17	0.15	0.15
Energy	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Equipment	0.10	0.10	0.11	0.10	0.10	0.10	0.11	0.10	0.11	0.10	0.10	0.10
Tooling	0.08	0.10	0.12	0.07	0.09	0.07	0.11	0.09	0.11	0.07	0.09	0.10
Building	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Maintenance	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Overhead	0.06	0.07	0.07	0.06	0.06	0.06	0.07	0.07	0.07	0.06	0.07	0.07
Total	**0.77**	**0.80**	**0.85**	**0.75**	**0.78**	**0.75**	**0.83**	**0.79**	**0.83**	**0.75**	**0.78**	**0.83**

Table 7-10. Incremental Fabrication Costs for Tubular Steel Variants (Normalized)

Incremental - Fabrication												
	Conv - Only	Sedan - Only	X-Over - Only	Conv & Sed		Conv & X-Over		Sedan & X-Over		All 3		
	Conv	Sedan	X-Over	Conv	Sedan	Conv	X-Over	Sedan	X-Over	Conv	Sedan	X-Over
Material	0.29	0.31	0.33	0.29	0.31	0.29	0.33	0.31	0.33	0.29	0.31	0.33
Labor	0.17	0.15	0.15	0.17	0.15	0.17	0.15	0.15	0.15	0.17	0.15	0.15
Energy	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Equipment	0.10	0.10	0.11	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Tooling	0.08	0.10	0.12	0.08	0.07	0.08	0.09	0.10	0.09	0.08	0.09	0.08
Building	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Maintenance	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Overhead	0.06	0.07	0.07	0.06	0.06	0.06	0.07	0.07	0.07	0.06	0.07	0.06
Total	**0.77**	**0.80**	**0.85**	**0.77**	**0.76**	**0.77**	**0.81**	**0.80**	**0.81**	**0.77**	**0.79**	**0.79**

Table 7-11. Shared Assembly Costs for Tubular Steel Variants (Normalized)

Shared - Assembly												
	Conv - Only	Sedan - Only	X-Over - Only	Conv & Sed		Conv & X-Over		Sedan & X-Over		All 3		
	Conv	Sedan	X-Over	Conv	Sedan	Conv	X-Over	Sedan	X-Over	Conv	Sedan	X-Over
Material	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Labor	0.23	0.25	0.29	0.21	0.23	0.21	0.27	0.23	0.27	0.22	0.24	0.28
Energy	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Equipment	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Tooling	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Building	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Maintenance	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Overhead	0.17	0.19	0.21	0.13	0.15	0.13	0.17	0.15	0.17	0.13	0.15	0.16
Total	**0.45**	**0.50**	**0.57**	**0.39**	**0.44**	**0.39**	**0.51**	**0.44**	**0.51**	**0.39**	**0.44**	**0.51**

Table 7-12. Incremental Assembly Costs for Tubular Steel Variants (Normalized)

Incremental - Assembly												
	Conv - Only	Sedan - Only	X-Over - Only	Conv & Sed		Conv & X-Over		Sedan & X-Over		All 3		
	Conv	Sedan	X-Over	Conv	Sedan	Conv	X-Over	Sedan	X-Over	Conv	Sedan	X-Over
Material	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Labor	0.23	0.25	0.29	0.23	0.23	0.23	0.27	0.25	0.27	0.23	0.23	0.28
Energy	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Equipment	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Tooling	0.02	0.02	0.02	0.02	0.01	0.02	0.02	0.02	0.02	0.02	0.01	0.02
Building	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Maintenance	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Overhead	0.17	0.19	0.21	0.17	0.12	0.17	0.14	0.19	0.13	0.17	0.12	0.15
Total	**0.45**	**0.50**	**0.57**	**0.45**	**0.40**	**0.45**	**0.47**	**0.50**	**0.47**	**0.45**	**0.40**	**0.49**

7.4 IP Beam Case Study – Supplemental Data

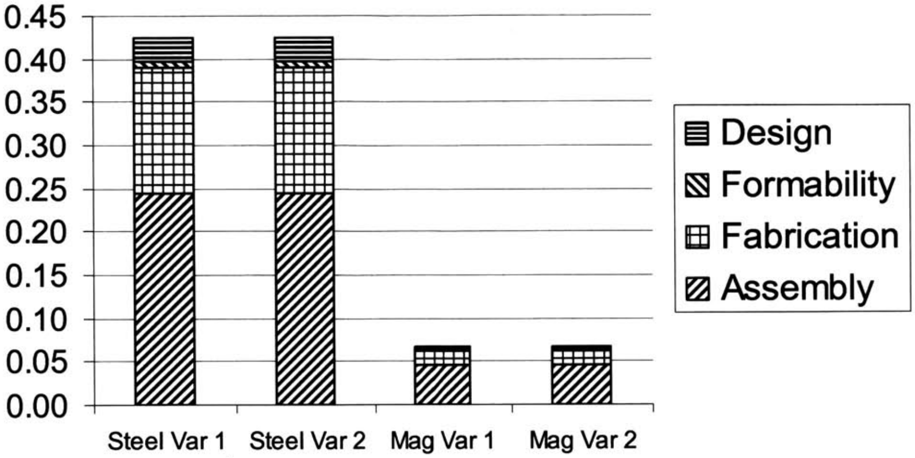

Figure 7-41. Standalone Development Costs for IP Beams

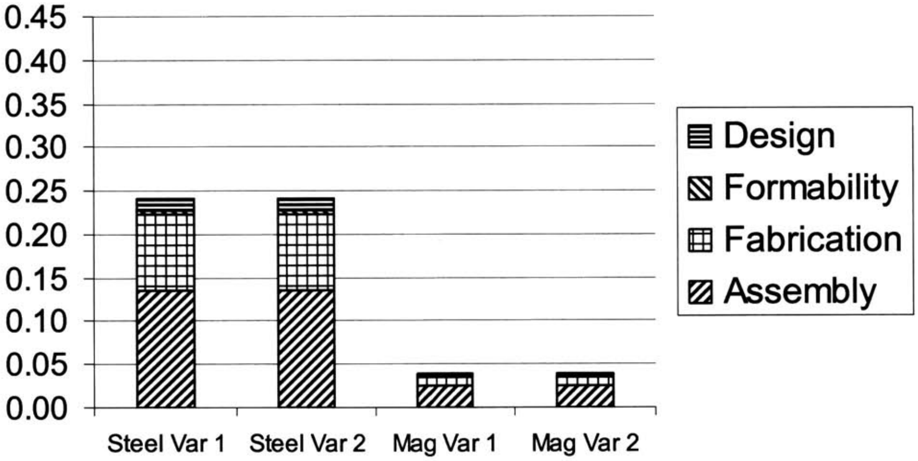

Figure 7-42. Shared Development Costs for IP Beams

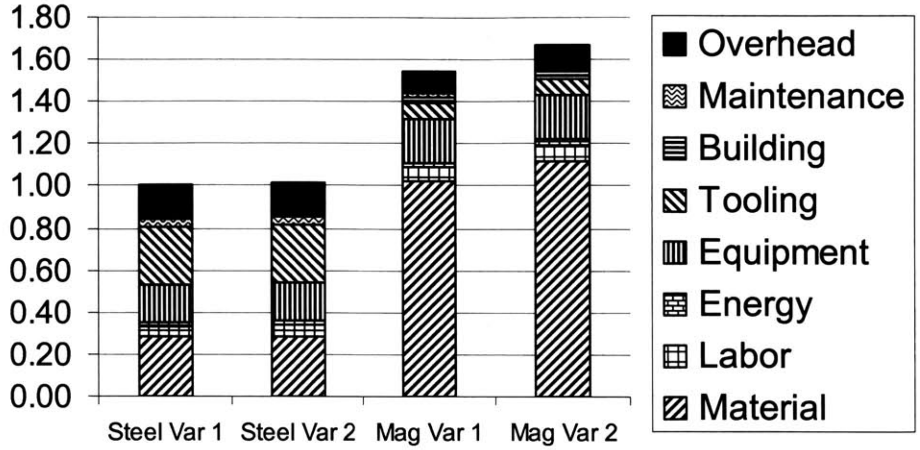

Figure 7-43. Standalone Fabrication Costs for IP Beams

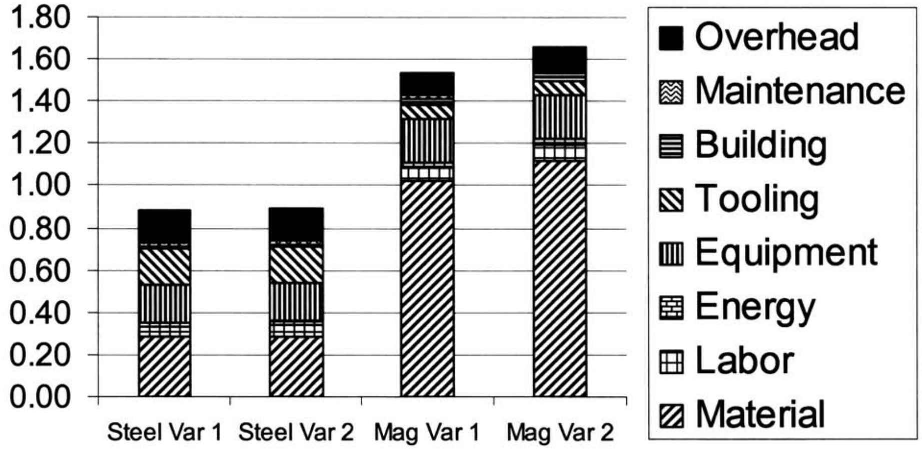

Figure 7-44. Shared Fabrication Costs for IP Beams

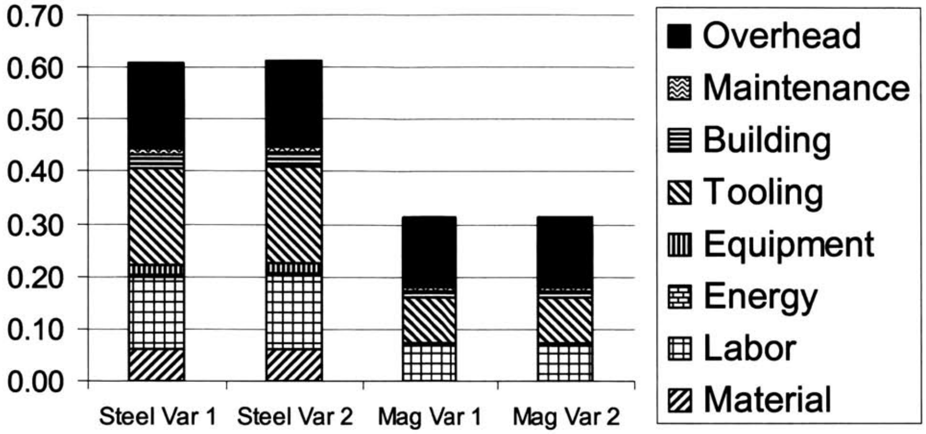

Figure 7-45. Standalone Assembly Costs for IP Beams

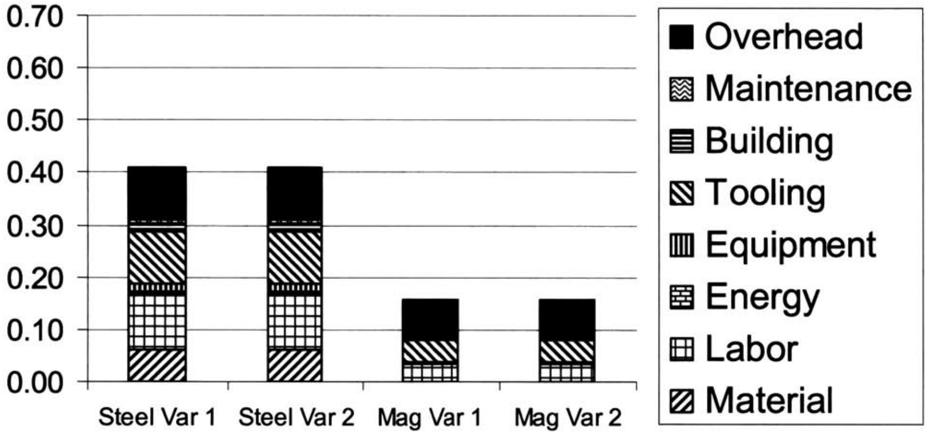

Figure 7-46. Shared Assembly Costs for IP Beams

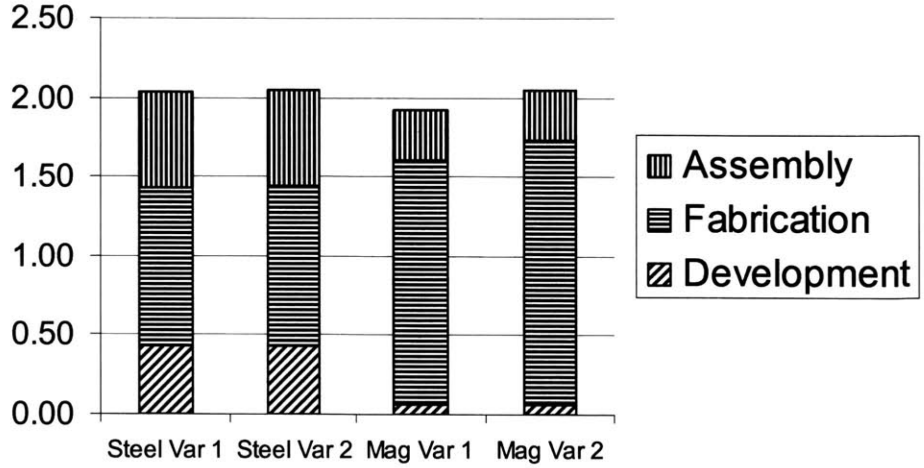

Figure 7-47. Standalone Total Costs for IP Beams

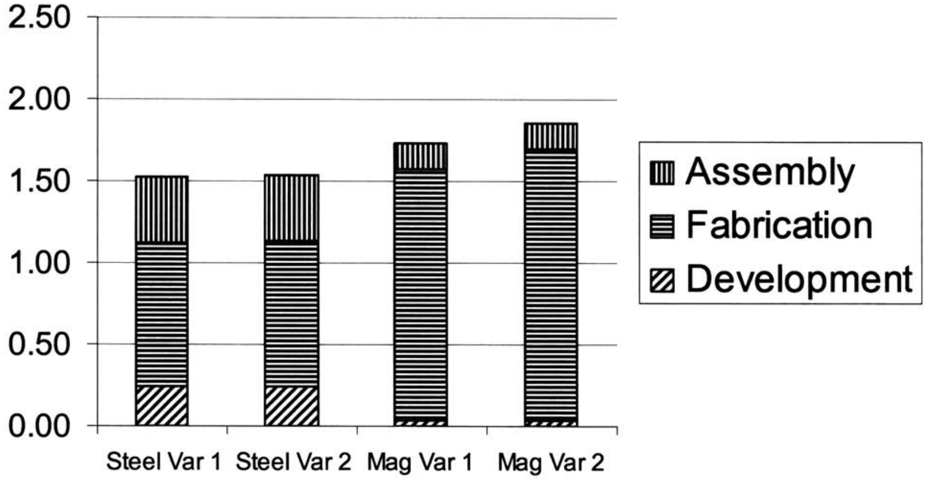

Figure 7-48. Shared Total Costs for IP Beams

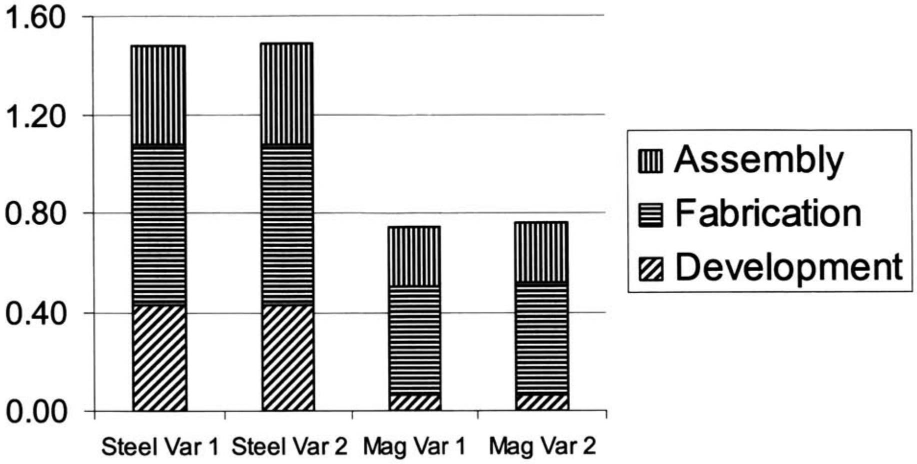

Figure 7-49. Standalone Total Fixed Costs for IP Beams

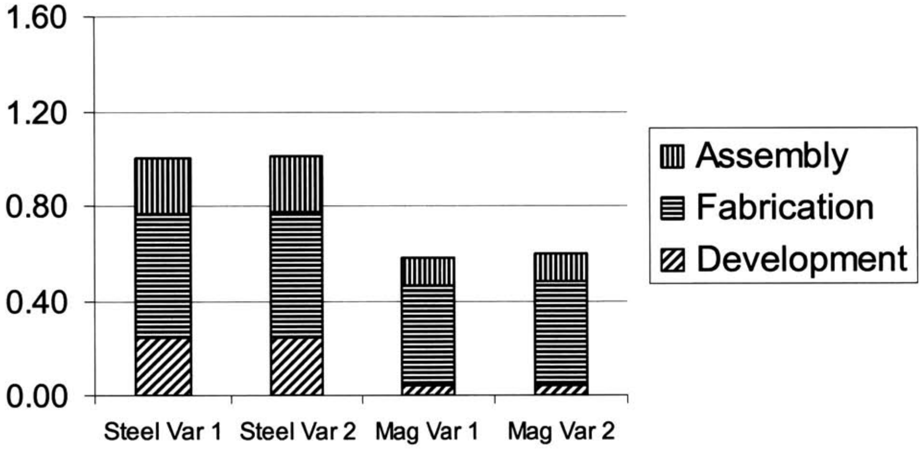

Figure 7-50. Shared Total Fixed Costs for IP Beams

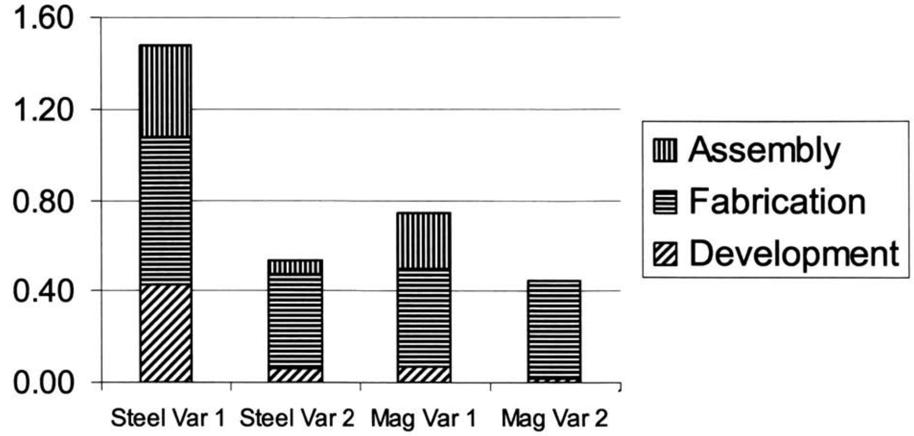

Figure 7-51. Incremental Total Fixed Costs for IP Beams

Table 7-13. IP Beam Development Cost Data (Normalized)

IP Beam - Development												
	Standalone		Standalone		Shared		Shared		Incremental		Incremental	
	Steel Var 1	Steel Var 2	Mag Var 1	Mag Var 2	Steel Var 1	Steel Var 2	Mag Var 1	Mag Var 2	Steel Var 1	Steel Var 2	Mag Var 1	Mag Var 2
Assembly	0.245	0.245	0.047	0.047	0.135	0.135	0.026	0.026	0.245	0.024	0.047	0.005
Fabrication	0.145	0.145	0.014	0.014	0.088	0.088	0.010	0.010	0.145	0.031	0.014	0.006
Formability	0.007	0.007	0.000	0.000	0.005	0.005	0.000	0.000	0.007	0.002	0.000	0.000
Design	0.027	0.027	0.005	0.005	0.014	0.014	0.004	0.004	0.027	0.001	0.005	0.003
Total	**0.42**	**0.42**	**0.07**	**0.07**	**0.24**	**0.24**	**0.04**	**0.04**	**0.42**	**0.06**	**0.07**	**0.01**

Table 7-14. IP Beam Fabrication Cost Data (Normalized)

IP Beam - Fabrication												
	Standalone		Standalone		Shared		Shared		Incremental		Incremental	
	Steel Var 1	Steel Var 2	Mag Var 1	Mag Var 2	Steel Var 1	Steel Var 2	Mag Var 1	Mag Var 2	Steel Var 1	Steel Var 2	Mag Var 1	Mag Var 2
Material	0.28	0.29	1.02	1.12	0.28	0.29	1.02	1.12	0.28	0.29	1.02	1.12
Labor	0.05	0.05	0.07	0.08	0.05	0.05	0.07	0.08	0.05	0.05	0.07	0.08
Energy	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Equipment	0.18	0.18	0.21	0.21	0.18	0.18	0.21	0.21	0.18	0.18	0.21	0.21
Tooling	0.28	0.28	0.07	0.08	0.17	0.17	0.07	0.07	0.28	0.07	0.07	0.06
Building	0.00	0.00	0.03	0.03	0.00	0.00	0.03	0.03	0.00	0.00	0.03	0.03
Maintenance	0.03	0.03	0.02	0.02	0.03	0.03	0.02	0.02	0.03	0.02	0.02	0.02
Overhead	0.16	0.16	0.11	0.11	0.14	0.15	0.11	0.11	0.16	0.13	0.11	0.11
Total	**1.00**	**1.01**	**1.54**	**1.67**	**0.88**	**0.89**	**1.53**	**1.66**	**1.00**	**0.77**	**1.54**	**1.65**

Table 7-15. IP Beam Assembly Cost Data (Normalized)

IP Beam - Assembly												
	Standalone		Standalone		Shared		Shared		Incremental		Incremental	
	Steel Var 1	Steel Var 2	Mag Var 1	Mag Var 2	Steel Var 1	Steel Var 2	Mag Var 1	Mag Var 2	Steel Var 1	Steel Var 2	Mag Var 1	Mag Var 2
Material	0.06	0.06	0.00	0.00	0.06	0.06	0.00	0.00	0.06	0.06	0.00	0.00
Labor	0.14	0.14	0.07	0.07	0.10	0.10	0.03	0.03	0.14	0.07	0.07	0.00
Energy	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Equipment	0.02	0.02	0.00	0.00	0.02	0.02	0.00	0.00	0.02	0.02	0.00	0.00
Tooling	0.18	0.18	0.09	0.09	0.10	0.10	0.04	0.04	0.18	0.01	0.09	0.00
Building	0.03	0.03	0.01	0.01	0.02	0.02	0.01	0.01	0.03	0.00	0.01	0.00
Maintenance	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.01	0.00	0.01	0.00
Overhead	0.17	0.17	0.13	0.13	0.10	0.10	0.07	0.07	0.17	0.03	0.13	0.00
Total	**0.61**	**0.61**	**0.31**	**0.31**	**0.41**	**0.41**	**0.16**	**0.16**	**0.61**	**0.20**	**0.31**	**0.00**

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