Quantifying the Effects of Parts Consolidation and Development Costs on Material Selection Decisions: A Process-based Costing Approach

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Abstract

Product designers must continually assess trade-offs among various performance attributes and cost. Materials choice can play an important role in that decision-making process. Materials affect many aspects of a product and firm – architecture, manufacture, and product performance. This paper examines the interrelationship of these early stage design choices through the application of process-based cost modeling. To capture the far-ranging effects of materials selection, models are presented which forecast the costs of development, manufacture, and assembly.

A case study is detailed concerning two alternative material options for an automotive instrument panel beam: a conventional design (i.e., stamped steel) and a die-cast magnesium design which affords significant parts consolidation. Results indicate that parts consolidation led to both lower assembly and development costs. These cost reductions are shown to be a direct result of the consolidation of parts in the magnesium design.

Keywords: Materials selection, cost, automobile, case study, parts consolidation

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1. Introduction

The goal of most firms is to deliver products that satisfy customer needs. Meeting these needs almost always requires design trade-offs involving conflicting or divergent goals such as mechanical performance vs. energy consumption or weight vs. durability (Ashby, 1999). One mechanism that designers have to accommodate divergent design objectives is materials substitution. Materials change can alter the available design space, enabling increased performance even across multiple performance criteria (e.g., higher strength and decreased weight). However, materials not only bring a bundle of physical properties, but can also radically change the set of appropriate manufacturing processes. This alters both the ultimate physical form of the product and the composition and configuration of the supply chain. These far-reaching implications are both the root cause of the transformative nature of materials, but also impede materials substitution. Analogously, if substitution is to occur, it must be able to be evaluated in the early stages of the development process when little information is known, but when decisions about form and processes are not yet set.

To realize this goal, the past decade has seen the emergence of robust tools to identify appropriate materials candidates, even with limited design information and these tools continue to improve (Ashby, 1999). However, in all cases, codified materials selection methods provide only limited insight into the universal performance requirement, cost. Once a set of candidate materials are identified, effective materials selection requires tools that provide quantitative insight into the economic implications of the materials alternatives. The purpose of this work is to present one such method that has proven effective in enabling economically-informed materials decisions and to explore the impact of extending that method to capture the implications of the product development process itself on the economically-preferred material alternative. In all, this paper will demonstrate that 1) that the addition of development cost significantly affects material technology economics (as opposed to previous analyses limited to fabrication and assembly costs); and 2) that process-based, generative cost models can provide quantitative insight into the impact of these effects even when limited design information is available (i.e., during early-stage design). To explore these various issues, a general model and a specific case study are presented. The latter examines two alternative material options for an automotive1 instrument panel beam: a conventional design (i.e., stamped steel) and a die-cast magnesium design.

2. Previous Work in the Economics of Technology Choice and Assessment

Although, in some cases, materials improve both performance and cost, this is frequently not the case (de Cillis, 2001; Shin et al., 2002), thus requiring that trade-offs be made among the goals of the project. Because of the extensive implications and, therefore, the complexity of materials choice, designers require analytical tools to accurately evaluate the benefits and costs of alternative materials. The absence of such tools leads to either cost constraints or asynchronous cost estimation both of which limit design options (Field et al., 2001; Noble and Tanchoco, 1990; Wei and Egbelu, 2000). 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 (Asiedu and Gu, 1998). This would allow the designer to make explicit trade-offs between certain features or product characteristics and their marginal cost (Noble and Tanchoco, 1990).

To make explicit trade-offs, designers require the ability to trace costs to specific design choices. Activity based costing (ABC) is a widely-cited method that traces costs to causal activities and processes (Angelis and Lee, 1996; Cleland, 2001; Cooper and Kaplan, 1988; Cooper and Kaplan, 1991). While ABC concepts are fundamental to effective decision making, their retrospective accounting approach makes them insufficient for evaluating innovative technological options like are associated with novel materials. Instead, ABC concepts must be augmented with predictive capabilities (Cooper and Kaplan, 1998); specifically, the ability to map product characteristics to physical and operational attributes of product realization.

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[1] The automotive industry provides a useful context in which to explore the trade-offs of materials, processes, and cost. The global automotive industry is very competitive; automotive OEMs have to deliver a wide range of safe, environmentally friendly, quality products, which customers value, and do so at low costs. The use of alternative materials and designs can relieve the tension between some of these conflicting goals, but this is rarely a complete solution.

Predictive cost modeling attempts to bridge this gap by projecting 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 a current product or process being studied and previous products or processes that have been completed to project costs (e.g., (Daschbach and Apgar, 1988)). Generative cost estimation projects costs based on production requirements and operational conditions (Weustink et al., 2000). The fact that variant-based costing relies on previous products makes it less useful for new technologies or technologies that create extensive difference from previous operating conditions. This characteristic makes variant-based methods, generally, less useful for contexts with rich sets of materials choices, because of the likely absence of strong manufacturing analogues. As such, the balance of this paper will focus on the application of generative costing methods to materials selection decisions.

Several generative models have been proposed for use in cost estimation of both manufacturing and assembly (Boothroyd et al., 1994; Leibl et al., 1999; Noble and Tanchoco, 1990; Shehab and Abdalla, 2001), however, there is no widely accepted and used system (Wei and Egbelu, 2000). Some researchers have applied generative models to select among alternative materials and manufacturing technologies. For example, 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 and time to market perspectives In the end, the use of generative cost models to support technology choice decisions has been shown, in some cases for processes not yet operating at full manufacturing scale. 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 (Jain, 1997). 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 (Kang, 1998). Other work has shown less ambiguous benefits of parts consolidation. 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% (Ernst, 1987).

This work presents a process-based, generative model and case analysis that complements and extends those in the literature to-date by 1) introducing a more operationally detailed algorithm for production resource estimation and 2) incorporating a generative model of product development cost. Together, these additional capabilities provide quantitative insight into a more complete range of cost consequences – fabrication, assembly, and development – across most of the dimensions of the design decision space including the technological– materials, architecture, and process; operational; and strategic – production volume – and can be applied during early stage design. The following section outlines the methods used here and highlights the above listed capabilities.

3. Quantitative Methods to Support Materials Technology Selection Decisions: Process–Based Cost Modeling

Process-based cost modeling (PBCM) is an early stage cost estimation tool that uses various part and process characteristics to project manufacturing, assembly, and, uniquely in this paper, product development costs.2 Process-based cost models for several manufacturing processes exist and have been used to answer numerous research questions around the comparison and selection of materials, processes, and architectures (Busch, 1987; Han, 1994; Jain, 1997; Kang, 1998; Kelkar, 2000). 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 1) correlating the effects of relevant physical parameters on the cost-determinant attributes of a process (e.g., cycle time, equipment performance requirements), 2) relating these processing attributes to manufacturing resource requirements (e.g., kg of material, number of laborers, number of machines and/or tools), and 3) translating these requirements to a specific cost (Kirchain and Field, 2001). The relationship between physical parameters and process characteristics is determined by using physical relationships and/or through statistical analysis.

[2] Although the method can be used to estimate other costs as well

The inputs required for a PBCM can be broken into four main categories: part and material related, process related, operational, and financial. As an example, for a metal stamping part, data such as material type, part size, complexity, and gage, would be used to project component specific processing characteristics including the required press tonnage and a line rate. These quantities could then be combined with operational information, such as available facility uptime, physical plant design, and production goals, to project the characteristics of a manufacturing operation capable of producing the part of concern. These characteristics would include the type and quantity of equipment employed, operating time, and the magnitude of variable factor inputs required to meet output goals. Finally, this projection of a capable manufacturing facility combined with factor prices and financial information can be combined to project manufacturing cost. A schematic of process based cost modeling can be seen in Figure 1, which shows the three key modeling steps leading from case description through process characteristics to operation characteristics to cost. For the analyses presented in this paper PBCMs of both sheet-metal stamping and die-casting were used.

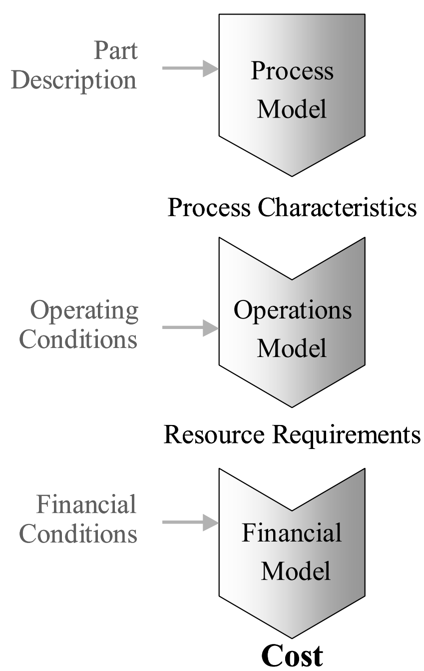

Figure 1: Schematic of Process-based Cost Modeling

To determine the total manufacturing cost for a product with multiple parts, the cost of assembly must be included. The process-based cost model of assembly used in the analysis herein was developed at the Materials Systems Laboratory at MIT and relies on relational data structures containing information about the assemblies to be analyzed, the joining methods required by these assemblies, process-specific information about joining methods, and operational conditions to estimate an assembly cost. This model has been employed to examine over fifty materials and architectural cases across the automotive industry (e.g. (Fixson, 2002; Fixson, 2004; Fixson, 2005; Fuchs, 2003; Jain, 1997; Kang, 1998; Kelkar et al., 2001; Kelkar, 2000; Roth and Shaw, 2002; Roth et al., 1998; Veloso, 2001)). The model requires that assemblies be described in terms of part count, joining intensity (i.e., length or number of joins), and joining methods to be employed. This information is used to project cost-determinant processing characteristics, such as equipment specifications and the amount of assembly time required, which are combined with operational specifications such as production volume and shift structure to project manufacturing resource requirements. Resource requirements, such as equipment, tooling, and consumables required, are then combined with financial assumptions and factor costs to project both fixed and variable costs. A schematic of the process-based cost model for assembly used in this analysis can be seen in Figure 2.

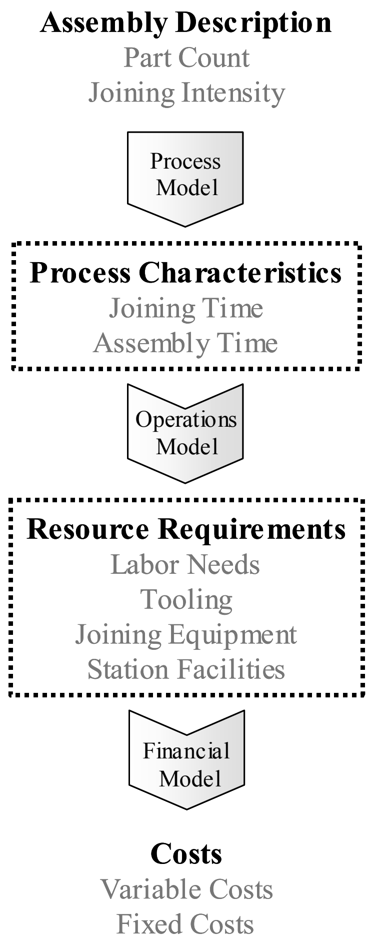

Figure 2: Schematic of Technical Cost Modeling for Assembly

A typical cost modeling analysis aimed at a technology selection question would examine parts fabrication costs; a more rigorous assessment would also include assembly costs for the alternative technologies (e.g. (Fixson, 1999; Jain, 1997; Kang, 1998; Kelkar, 2000; Lokka, 1997)). In contrast, some assessments might look at other isolated costs such as the cost of development or development lead time. To capture the total cost of a development project and ensure appropriate trade-offs among competing options, fabrication, assembly, and development costs of the project should be examined. A process-based cost model of the development process is used in this paper that includes both direct development costs (direct development labor) as well as indirect costs (overhead, computers, prototypes, etc.). A summary of the process-based cost model of the development process used in this work is given in the next section. See Johnson (Johnson, 2004) for a more detailed explanation of the development model.

4. Model Summary

4.1 Process-based Cost Model of Fabrication and Assembly

An analytical summary of the process-based cost models used for part fabrication and assembly in this work is detailed in Appendix A.

4.2 Process-based Cost Model of the Development Process

Development is a multidisciplinary activity that encompasses many areas. To account for every cost associated with development would be a near impossible task. The purpose of the model constructed for this study was to account for a large majority of the costs associated with development. After discussions with design managers at a major automotive OEM, four key cost categories were identified. These included labor, equipment, software, and overhead/ supervision. The process-based cost model of the development process projects these costs for the stages of the development process shown in Figure 3.

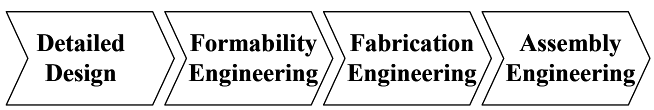

Figure 3. Stages of the product development process

As the purpose of this model is to project development costs in the context of production costs, it was import for development costs to be allocated to specific components and assemblies. To further maintain a consistent representation, these costs were also amortized over the product lifetime and divided by the projected annual production volume. This allowed development costs to be compared with manufacturing costs on a per piece part basis. The calculation of these costs is shown in Equations 1 to 4:

$$C_{i,Total} = C_{i,Labor} + C_{i,Equipment} + C_{i,Software} + C_{i,Overhead} \quad \text{Eq. 1}$$

$$C_{i,El} = {AC_{i,EL}}/{PV_i} \quad \text{Eq. 2}$$

$$AC_{i,El} = TC_{i,El} \times crf\,(product\,life) \quad \text{Eq. 3}$$

$$crf\,(s) = \frac{[d(1+d)^s]}{[(1+d)^s - 1]} \quad \text{Eq. 4}$$

where C_i = unit cost ($ per saleable unit) per component, i; AC_i = annual cost ($), PV_i = annual production volume (saleable number produced), TC_i = total cost over product life, and $crf(product\ life)$ = capital recovery factor with s = product life and d = the periodic discount rate; and El = cost element (Labor, Equipment, Software, Overhead).

Using the above definitions, the total cost of labor is calculated as shown in Equations 5 and 6:

$$TC_{i,Labor} = wage \times TDH_i \quad \text{Eq. 5}$$

$$TDH_i = \left(reqRTH_i \big/ designer\ productivity \right) \quad \text{Eq. 6}$$

where TDH_i is the total paid design time required for component i; $reqRTH_i$ is the projected raw tube hours (computer design time) required to design and modify component i; and *designer productivity* is the ratio of direct design time to total paid time doing design related activities which accounts for other non-direct design related activities (e.g. meetings).

The total cost for design related equipment (e.g. that related to prototyping and computers) is calculated using Equations 7 to 9:

$$TC_{i,Equipment} = Inv_{i,Equipment} \times crf\left(s_{i,Equipment}\right) \times LR_i \quad \text{Eq. 7}$$

$$LR_i = TDH_i \big/ availLT \quad \text{Eq. 8}$$

$$availLT = DPY \cdot (24 - NS - UB - PB - UD) \quad \text{Eq. 9}$$

where LR_i = number of required parallel sets of equipment to design component i

Inv = non-periodic investment to be allocated,

s = the productive life of the design equipment.

DPY = operating days per year for the design shop,

NS = no operations (hr/day the plant is closed),

UB = unpaid breaks (hr/day),

PB = paid breaks (hr/day), and

UD = Unplanned downtime (hr/day).

The total cost for software (e.g. CAD and finite element programs) for the development of component i is calculated using Equation 10 with all other variables as defined above:

$$TC_{i,Software} = UC_{Software} \times LR_i \quad \text{Eq. 10}$$

where *UC* is the cost of a software license per seat per year.

To capture the cost of indirect labor (e.g. managerial oversight), overhead is calculated using Equation 11:

$$TC_{i,Overhead} = Oh \times reqRTH_i \quad \text{Eq. 11}$$

where *Oh* is the overhead factor.

The fundamental determinant of each of the cost elements is $reqRTH_i$, this is the projected amount of engineering effort (i.e., required raw tube hours representing the expected person-hours of design time). This quantity is projected for each stage of the development process using a set of empirically derived models. These models were developed using data gathered from a large automotive OEM. These data consisted of part and development process characteristics along with the amount of engineering effort required for the development of that part or assembly at that stage of the development process. Linear regression analysis was then used to relate part and assembly characteristics to engineering effort. Table 1 shows a breakdown of equations used to project engineering effort for each stage.

Table 1. Summary of multiple linear regression analyses for various development stages (standard errors are represented in parentheses)

	Intercept	Size (dm^3)	Complexity	Project Overlap	No. of Parts	R^2	F-Stat
Design - Main	0.230	0.002	--	-0.031	--	0.47	17.3
	(0.050)	(0.000)	--	(0.018)	--		
Formability	-0.022	0.001	0.235	--	--	0.76	37.9
	(0.202)	(0.000)	(0.072)	--	--		
Fabrication	-0.026	0.001	0.210	--	--	0.96	129
	(0.169)	(0.000)	(0.061)	--	--		
Assembly[1]	--	--	0.119	--	0.070	0.88	65.4
	--	--	(0.053)	--	(0.016)		

[1] R^2 for assembly linear regression should not be compared to those which have intercepts.

In Table 1, the first listed variable is Size (i.e., the size of the part), defined as the volume of the smallest bounding box which would encompass the part (Note that this variable was not significant for the assembly analysis). The second listed variable is the geometric complexity of the part or assembly based on a five-point scale. As examples, a simple part, such as a bracket, is a "one", while a complex part, such as a floor pan, is a "five". In the case of assemblies, a simple bracket assembly is a "one" while a complex motor compartment or bodyside assembly is a "five". Project overlap is an estimate of the amount of overlap for the design project (subassembly of parts that the part in question interacted with) that included this part. This indicates how much information the designer has about other interacting parts prior to beginning 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). The final variable is the number of parts in an assembly.

To explore fully the usefulness of such modeling methods to support combined materials and architectural design decisions, the models were exercised against a detailed case study. The next section details that case.

5. Case Study: Economic Competitiveness of Two Competing Instrument Panel Designs

To assess the effects of material choice, as well as the suitability of process-based cost modeling to address this issue, two alternative instrument panel (IP) beam designs were analyzed using the models described in the preceding section: 1) a tube-based steel design[3] and 2) a die-cast magnesium design which affords significant parts consolidation.

5.1 Case Data and Assumptions

The designs of both alternatives were developed with the input of designers at a major US automaker. Although representative of designs used in a mid-sized sedan, these designs do not reflect components within any specific vehicle. The steel IP beam (subsequently denoted Steel IP) consisted of a tubular structure with over two-dozen brackets attached. The magnesium design comprised a primary die cast magnesium structure (denoted Mg IP) with two additional unique bracket pairs. Table 2 details key

[3] Most vehicles today use similar tube-based steel instrument panel beams.

physical and processing information about the two designs. Processing information for these parts was estimated using the process-based models. Notably, the major die cast part is projected to have a production rate approximately two to three times slower than that of the analogous steel components. Table 3 provides general operational and financial assumptions made for the purposes of modeling manufacturing and cost. All such inputs are representative of conditions experienced by automotive manufacturers in developed countries, but do not reflect the operating conditions of any specific firm.

Table 2. Baseline Case Component Geometric and Process Descriptions

Name	Manufacturing Process	Mass (kg)	Reject Rate	Trim Loss	Melt Loss	Cycle Time (sec)	Relative Tool Investment
Magnesium Beam Parts							
Main IP Structure	Die Casting	8.1	1.0%	2%	3%	142	1.00
Average Bracket (4 Total)	Stamping	0.2	1.0%	20%	0%	2	0.06
Steel Beam Parts							
Reinforcement IP Upper	Tube Bending	2.0	0.2%	5%	0%	70	0.06
Reinforcement IP Lower 1	Tube Bending	0.4	0.2%	5%	0%	49	0.04
Reinforcement IP Lower 2	Purchased Tube	0.3	N/A	N/A	N/A	N/A	N/A
Average Bracket (27 Total)	Stamping	0.3	1.0%	20%	0%	2	0.07

Table 3. Baseline Model Inputs Used in Analyses

Model Inputs	
Annual Production Volume	75000 parts/yr
Days per Year	235 days/yr
Wage (including benefits)	50 $/hr
Unit Energy Cost	0.05 $/kWhr
Periodic Discount Rate	10 %
Indirect workers/ Direct Worker (part fabrication)	0.25
Indirect workers/Line (part fabrication)	1
Building Unit Cost	1200 $/sqm
Product Life (Tooling Life)	5 yrs
Equipment Life	15 yrs
Building Life	40 yrs
Equipment	Non Dedicated
Buildings	Non Dedicated
Downtimes:	
Hours Per Day	7 hrs/day
Worker unpaid breaks	1 hrs/day
Worker paid breaks	1.2 hrs/day
Magnesium Price	$3.10 /kg
Magnesium Scrap Price	$2.30 /kg
Steel Sheet price	$0.81 /kg
Steel Tube Price	$1.30 /kg
Steel Scrap Price	$0.10 /kg

5.2 Results

Using the model summarized in the previous section, development, part fabrication, and assembly costs for the two design alternatives were evaluated. Specific features of each result are presented before discussing the implications of the combined cost.

Manufacturing Costs: Parts Production and Assembly

As seen in Figure 4, the fabrication cost of the steel IP beam is dominated by fixed costs at 75,000 units per year. These high fixed costs are dominated by tool cost, but other fixed costs include administrative overhead as well as allocated equipment and facility investments. Steel IP tooling costs are driven by tool investments for the numerous stamped brackets. Although, these components are small and simple, the shear number of required brackets dictates a significant tooling investment. In aggregate, the estimated tooling investment for the steel IP beam is almost twice that of the magnesium IP beam. In contrast, magnesium IP costs are dominated at most production volumes by variable costs, nearly 90% of which come from materials expenditures. Low part counts as well as the inherently near-net shape characteristic of die-casting leads directly to lesser tooling requirements and, therefore, to lower tooling investment costs. Unfortunately, these same traits do nothing to reduce the burden of the high unit cost of magnesium, which drives the high production costs for this design. The significance of variable costs implies that the magnesium IP beam will become less economically competitive at higher production volumes. The results shown in Figure 5 are consistent with this expectation, although the variation in cost difference is small over the range of production volumes investigated.

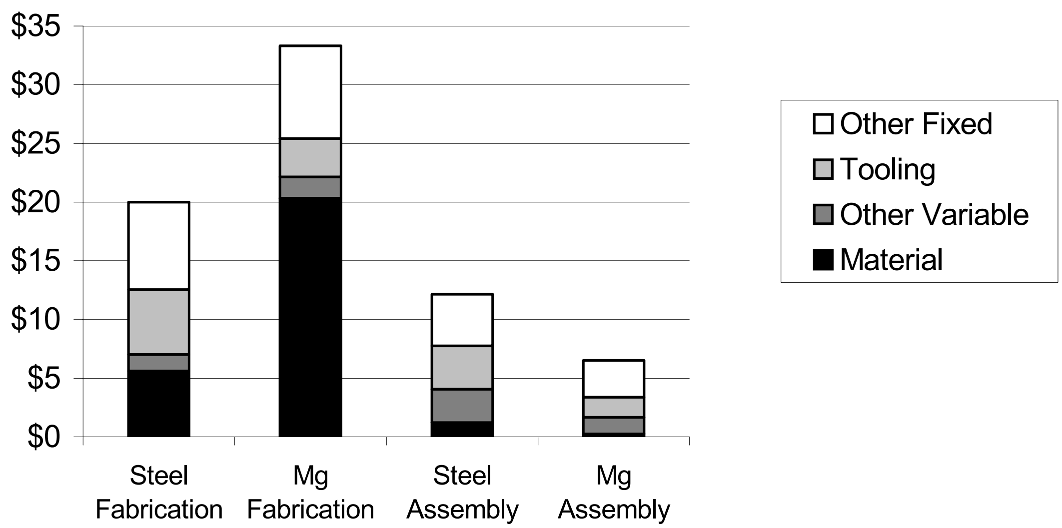

Figure 4: Traditional Process-based Unit Cost Comparison for Magnesium and Steel IP Beams at 75,000 Units Per Year