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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.

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, 2005). 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, 2005). 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 explore the use of one such method that has proven effective in enabling economically-informed

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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. Although several authors have discussed how development economics could vary as product characteristics change (Thevenot and Simpson, 2006), none have carried out a direct quantitative assessment of that effect (relying instead on indirect indicators such as component commonality). As such, it has not been possible previously to characterize precisely what types of technologies would be translate into additional development cost burden and whether that burden would be significant relative to more conventional costs. It is expected that the significance of development cost to any technology selection decision will grow as product life-cycles shrink (Carrillo and Franza, 2006; Ceglarek et al., 2004; Ottosson, 2004; Sherman et al., 2000).

With regard to these issues, this paper will demonstrate three effects that are previously unexplored in the literature, including that (1) development cost can vary across materials technologies; (2) the addition of development cost can significantly affect relative material technology economics, altering the economically preferred technology compared to previous analyses limited to fabrication and assembly costs; and (3) 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 automotive[1] instrument panel (IP) beam: a conventional design (i.e., stamped steel) and a die-cast magnesium design. The nature of case analysis precludes fully generalized conclusions, but the results shown herein suggest the potentially significant role of development costs in the materials selection decision process.

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; Houseman et al., 2008; Kaufmann et al., 2008; 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 (Cavalieri et al., 2004; Curran et al., 2004; Newnes et al., 2008; Niazi et al., 2006). A valuable cost estimation tool would consider all aspects of a products' life, from development until disposal (Asiedu and Gu, 1998; Kaufmann et al., 2008; Newnes et al., 2008). 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 (Brierley et al., 2006; Cooper and Kaplan, 1988, 1991; Niazi et al., 2007). 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.

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 (Curran et al., 2004; Niazi et al., 2006). 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., Cavalieri et al., 2004; Daschbach and Apgar, 1988; Wang et al., 2007; Zhang and Fuh, 1998). Generative cost estimation projects costs based on production requirements and operational conditions (Curran et al., 2004; Niazi et al., 2006; 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 (Niazi et al., 2006). 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., 2002; Leibl et al., 1999; Noble and Tanchoco, 1990; Shehab and Abdalla, 2001), however, there is no widely accepted and used system (Curran et al., 2004; Niazi et al., 2006; Wei and Egbelu, 2000). Some researchers have applied generative models to select among alternative materials and manufacturing technologies. For example, Hu and Poli (1997a, b) 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, generative cost models have been shown be useful to support technology choice decisions, in some cases for processes not yet

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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.

operating at full manufacturing scale. Jain (1997) 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. Kang (1998) 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. Other work has shown less ambiguous benefits of parts consolidation. Ernst (1987) 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%. More recently, similar models have been developed to examine the production of many technologies including both structural (Fuchs et al., 2008; Ruffo et al., 2006) and electronic components (Fuchs et al., 2006; Singer, 2004).

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; Fuchs et al., 2006, 2008; 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 (Field et al., 2007; Kirchain and Field, 2001). The relationship between physical parameters and process characteristics is determined by using physical relationships and/or through statistical analysis.

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 can be combined with factor prices and financial information to estimate manufacturing cost. A schematic of PBCM can be seen in Fig. 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.

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

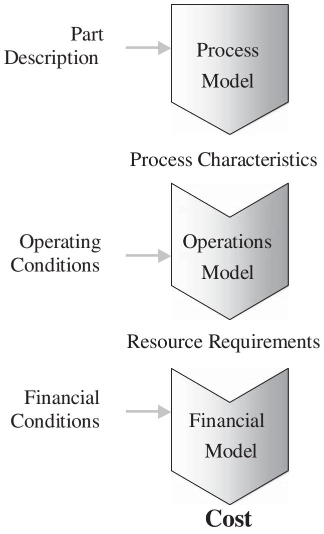

Fig. 1. Schematic of process-based cost modeling.

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

over fifty materials and architectural cases across the automotive industry (e.g., Fixson, 2004, 2005; Fuchs et al., 2008; Jain, 1997; Kang, 1998; Kelkar et al., 2001; 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 Fig. 2.

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 (2004) for a more detailed explanation of the development model.

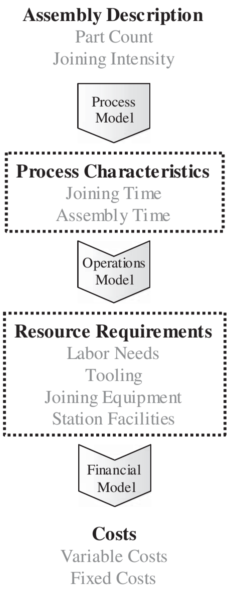

Fig. 2. Schematic of technical cost modeling for assembly.

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 tasks. 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 Fig. 3.

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 Eqs. (1)–(4):

$$C_{i,Total} = C_{i,Labor} + C_{i,Equipment} + C_{i,Software} + C_{i,Overhead} \tag{1}$$

$$C_{i,El} = AC_{i,EL}/PV_i \tag{2}$$

$$AC_{i,El} = TC_{i,El} \times crf(s) \tag{3}$$

$$crf(s) = \frac{[d(1+d)^s]}{[(1+d)^s - 1]} \tag{4}$$

where C_i is the unit cost ($ per saleable unit) per component, i; AC_i the annual cost ($), PV_i the annual production volume (saleable number produced), TC_i the total cost over product life, $crf(s)$ the capital recovery factor with s is the product life, d the periodic discount rate; and El the cost element (labor, equipment, software, overhead).

Using the above definitions, the total cost of labor is calculated as shown in Eqs. (5) and (6):

$$TC_{i,Labor} = wage \times TDH_i \tag{5}$$

$$TDH_i = (reqRTH_i/dp) \tag{6}$$

where TDH_i is the total paid design time required for component i; $reqRTH_i$ the projected raw tube hours

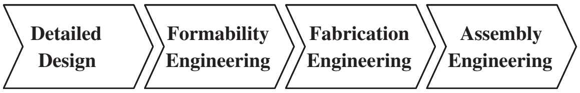

Fig. 3. Stages of the product development process.

(computer design time) required to design and modify component i; and designer productivity (dp) 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).

Aside from development labor, all other development costs (equipment, software, and supervisory labor) derive from the use of resources that can be and are used across many different development projects. In this sense, accounting for the cost of these resources requires some scheme by which they are allocated to individual development projects and activities. The literature suggests many bases that can be used for cost allocation including labor hours, machine hours, materials cost, production volume, or product margin (Brierley et al., 2006; Niazi et al., 2007). In each case, resource cost is allocated to an activity in terms of the fraction of the given basis attributable to that activity. Generally, costing systems enable more effective decision-making when the allocation basis reflects cost causality (Cooper and Kaplan, 1988, 1991).

In light of this goal, the authors chose to use machine time (i.e., $reqRTH_i$) to allocate development equipment, software, and supervisory labor within the model. This basis is compared against an approximated *normal capacity* (Brierley et al., 2006) ($\widetilde{availLT}$ below) which attempts to approximate the expected possible usage of supporting resources per year across all activities. This basis seems appropriate in this case because the extent of supporting resources (including equipment, software, and supervision) is expected to scale most strongly with the number of design professionals that use those resources and, therefore, with the amount of designer time required. Additionally, a time-based allocation scheme provides the benefit of not requiring information on other products or activities going on within the facility. To allocate according to profit margin or production volume, one needs to know the margin or volume for all activities sharing a resource. In the case of time, one simply needs to know the extent to which that resource is available. Despite these perceived advantages, future work should test the strength of this causality and, therefore, the implication of this allocation scheme on the observed results and conclusions.

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

$$TC_{i,Equipment} = Inv_{i,Equipment} \times crf(s_{Eq}) \times LR_i \tag{7}$$

$$LR_i = TDH_i/availLT = reqRTH_i/\widetilde{availLT} \tag{8}$$

$$\widetilde{availLT} = availLT \cdot dp = (DPY \cdot (24 - NS - UB - PB - UD)) \cdot dp \tag{9}$$

where Inv is the non-periodic investment to be allocated, s_{Eq} the productive life of the design equipment. LR_i the number of required parallel sets of equipment to design component i, $\widetilde{availLT}$ the productivity adjusted, annual time available to utilize equipment, DPY the operating days per year for the design shop, NS the no operations (h/day the plant is closed), UB the unpaid breaks (h/day), PB the paid breaks (h/day), and UD the unplanned downtime (h/day).

In the above, the quantity $\widetilde{availLT}$ represents the normal capacity of the design equipment for development work in any given development stage. That is approximately the number of hours the equipment could typically be used during a year. Beyond accounting for lost possible productive time in the form of design shop closings, breaks, and equipment breakdown, adjusting this figure by designer productivity captures a reality of the development process insofar as not all time can be spent actively designing parts.

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

$$TC_{i,Software} = UC_{Software} \times LR_i \tag{10}$$

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 Eq. (11):

$$TC_{i,Overhead} = Oh \times reqRTH_i \tag{11}$$

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 presents a breakdown of equations used to project engineering effort for each stage.

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.

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 (0.050)	0.002 (0.000)	– –	−0.031 (0.018)	– –	0.47	17.3
Formability	−0.022 (0.202)	0.001 (0.000)	0.235 (0.072)	– –	– –	0.76	37.9
Fabrication	−0.026 (0.169)	0.001 (0.000)	0.210 (0.061)	– –	– –	0.96	129
Assembly[a]	– –	– –	0.119 (0.053)	– –	0.070 (0.016)	0.88	65.4

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

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 IP designs

To assess the effects of material choice, as well as the suitability of PBCM to address this issue, two alternative 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 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.

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.

5.2.1. Manufacturing costs: parts production and assembly

As seen in Fig. 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 Fig. 5 are consistent with this expectation, although the variation in cost difference is small over the range of production volumes investigated.

As shown in Fig. 5, across the production volume scenarios explored, the assembly costs for the magnesium beam are lower than those of the steel beam. This would be expected, given the considerable parts consolidation and the associated reduced assembly content in the magnesium IP beam. Comparing the two designs, the

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

Table 2
Baseline case component geometric and process descriptions.

Name	Manufacturing process	Mass (kg)	Reject rate (%)	Trim loss (%)	Melt loss (%)	Cycle time (s)	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	N/A	2	0.06
Steel beam parts							
Reinforcement IP upper	Tube bending	2.0	0.2	5	N/A	70	0.06
Reinforcement IP lower 1	Tube bending	0.4	0.2	5	N/A	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	N/A	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 $/h
Unit energy cost	0.05 $/kW h
Periodic discount rate	10%
Indirect workers/direct worker (part fabrication)	0.25
Indirect workers/line (part fabrication)	1
Building unit cost	1200 $/m^2
Product life (tooling life)	5 yr
Equipment life	15 yr
Building life	40 yr
Equipment	Non-dedicated
Buildings	Non-dedicated
Downtimes	
Hours per day	7 h/day
Worker unpaid breaks	1 h/day
Worker paid breaks	1.2 h/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

magnesium beam requires only 12 rivets, compared to the steel design's 74 spot welds. At 75,000 units per year, this reduced content is modeled to translate into an assembly line for the magnesium design of only 2 stations. At that same production volume, the steel design is modeled to require 4 stations. These differences as well as the associated reduced equipment and manpower requirements translate into an assembly cost savings of 40–70% for the magnesium IP design compared to the steel IP depending on the production volume (cf. Fig. 5). Fig. 5 also shows the effect of production volume on the combined fabrication and assembly costs (labeled total manufacturing) of the two alternative IP beam designs for baseline factor price and operational conditions. At very low production volumes (i.e., less that 30,000 units per year) the fabrication and assembly costs of the magnesium IP beam are modeled to be lower than that of the steel IP, with this advantage growing as production volume drops. Such behavior arises due to the higher investment costs associated with the steel option. However, as higher production volumes allow for more effective utilization of fixed investments, steel IP costs drop, eventually making it the lower cost option. In fact, at production volumes of 75,000 units per year, manufactured cost (i.e., parts production plus assembly) for the magnesium IP is almost 30% higher than the steel analog. Furthermore, this differential continues to grow, albeit gradually, stabilizing at production volumes above 200,000 units per year at a premium of over 35%.

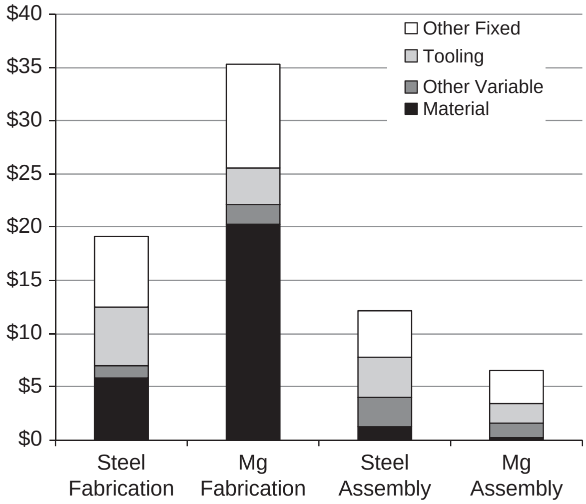

Fig. 4. Traditional process-based unit cost comparison for magnesium and steel IP beams at 75,000 units per year.

5.2.2. *Development costs*

Using the model summarized previously, the development costs for the two IP designs were projected. It is important to note that especially for the magnesium design, which is a clear departure from more conventional designs, it would not be possible to consult existing accounting information to estimate development costs. Furthermore, because the magnesium design is so radically different than the incumbent (5 components vs. 30 components), simple historic extrapolation is unlikely to be informative. The modeled development costs for the two designs are shown in Fig. 6.

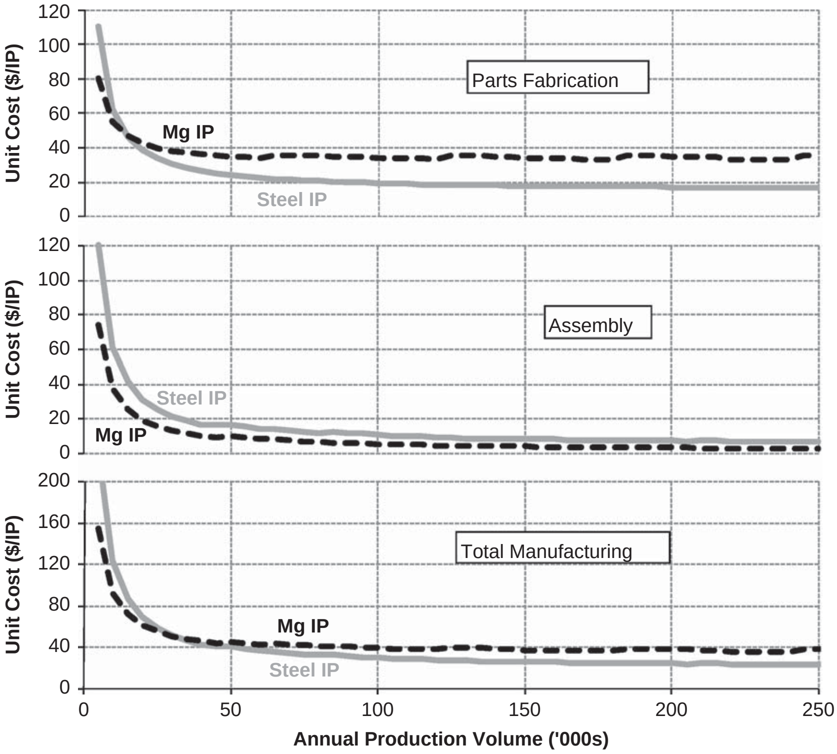

Fig. 5. Fabrication and assembly cost as a function of annual production volume.

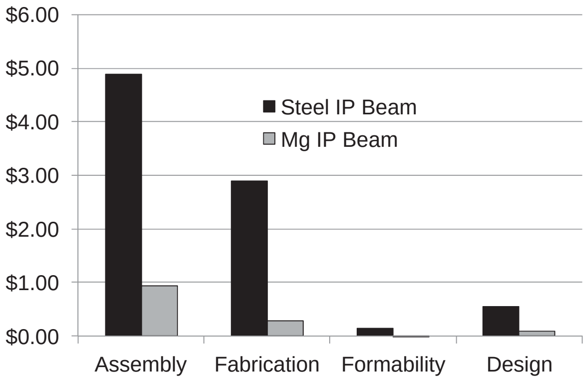

Fig. 6. Unit development costs for alternative IP beam designs at 75,000 units per year.

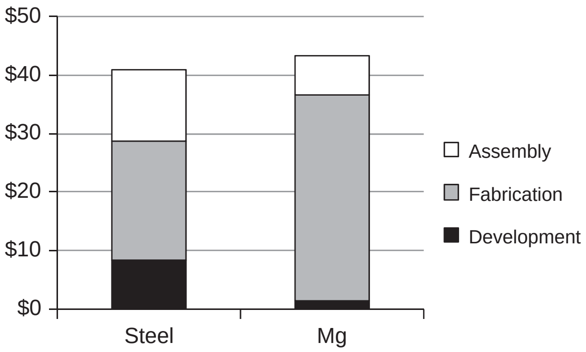

Fig. 7. Total costs for alternative IP beam designs.

Interestingly, although the complex die-casting is estimated to demand more than three times the development effort than the analogous steel component (i.e., the primary structural beam), the development cost for the overall magnesium design is much less. In aggregate, total development costs for the whole steel IP were over six times higher than those for the whole magnesium IP. As Fig. 6 makes clear, this difference is driven primarily by large additional fabrication and assembly development effort required by the steel IP. This disparity emerges primarily due to the larger number of parts and more complex assembly process required for the steel IP beam.

5.2.3. Total cost: parts production, assembly, and development

Notably, the development savings detailed in Fig. 6 are sufficient to drive the total cost of the magnesium IP design to within 5% of those of the steel design when compared at 75,000 units per year (see Fig. 7). In fact, the inclusion of development costs, a form of fixed cost, makes the magnesium design more competitive at all production volumes (cf. Figs. 5 and 8) and the least cost option across a broader range of conditions (as compared to the when development costs are omitted). Specifically, development cost shifts the point of cost parity between the two designs to almost 70,000 units per year (as shown

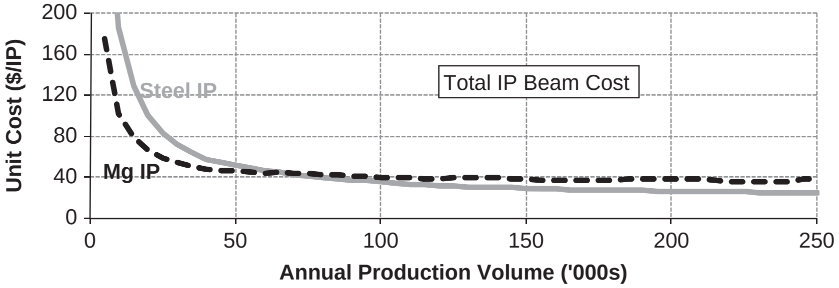

Fig. 8. Total IP beam unit cost as a function of annual production volume.

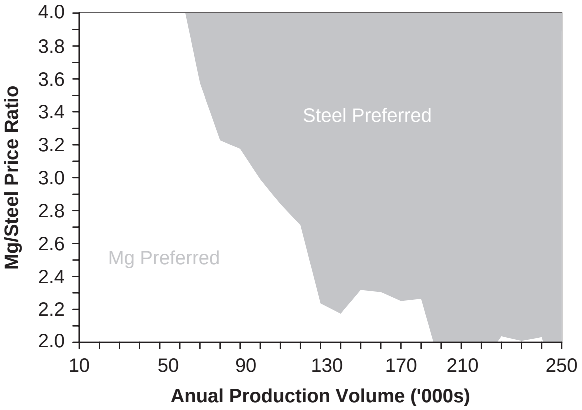

Fig. 9. Preferred material choice as a function of relative material prices and annual production volume.

in Figs. 5 and 8) from approximately 30,000 units per year when only parts production and assembly costs are considered. At production volumes below this, the models would project the magnesium design to be economically-preferred.

5.2.4. *Sensitivity analyses*

Although the inclusion of development cost indicates a previously unforeseen advantage for the magnesium design, the specifics of this advantage are sensitive to key assumptions within the modeling. Fortunately, the operational detail of the process-based models used in this analysis make it trivial to quantify this sensitivity. Fig. 9 addresses one of the largest sources of uncertainty that confronts this particular materials technology assessment: material prices. The relative competitive position of the incumbent steel design is strongly tied to the prevailing material prices. As the ratio of magnesium price to steel price decreases, the maximum production volume for which the magnesium design is projected to be the less costly option increases. If the ratio of magnesium price to steel price drops below 2.2, the magnesium design is projected to be the less costly design option for the majority of modeled production volumes.

Another advantage for the magnesium design is its limited number of parts. The steel design is projected to be more costly at lower production volumes due to significant investment associated with the larger number of parts. To analyze the effects of parts consolidation present in the magnesium beam design, scenarios were modeled which investigated the effects of splitting the magnesium design into an increasing number of parts. Notably, such changes affect not only the design costs (cf. Table 1), but also fabrication cost (due to increasing tool investment) and assembly cost (due to increasing assembly content). The specific characteristics of the modeled scenarios are presented in Table 4.

The results for the modeled scenarios are shown in Fig. 10. As expected, as the number of parts in the magnesium IP beam increase, the annual production volume at which it achieves cost parity with the steel IP beam design decreases. When the magnesium IP beam is segmented into more than ten parts, the steel design becomes the less costly options at all modeled production volumes. Clearly, the consolidation of parts in the magnesium design is the major driver of its cost competitiveness when compared to the steel design.

6. Conclusions

Changing materials can alter product performance, manufacturing processes, and even product architecture. This makes it difficult to assess the real economic implications of materials choice. Understanding these implications requires analytical tools that are both generative and capable of addressing a broad scope of activities. Process-based cost models have proven to fit this need for examining materials and other design options for single components and groups of components within a single subassembly. This work has demonstrated the extension of process-based cost models to comprehend changes in the development process so as to more effectively examine materials technology choice questions.

In applying these extended cost models to the study of competing magnesium and steel component designs, it was projected that the magnesium design reduced development, production tooling, and assembly cost. These savings emerged despite the increased complexity of the primary magnesium structure and were driven primarily due to parts consolidation. Notably, the projected development cost reduction would make the magnesium design more competitive than in a typical cost evaluation examining only production and assembly

Table 4
Variables for segmented magnesium IP beam scenarios.

Number of IP beam segments	IP beam part length (mm)	Beam complexity	Number of equivalent spots	Parts in assembly	Assembly complexity
1	1446	4	12	5	1
2	723	4	14	6	1
5	289	3	20	9	2
10	145	2	30	14	3

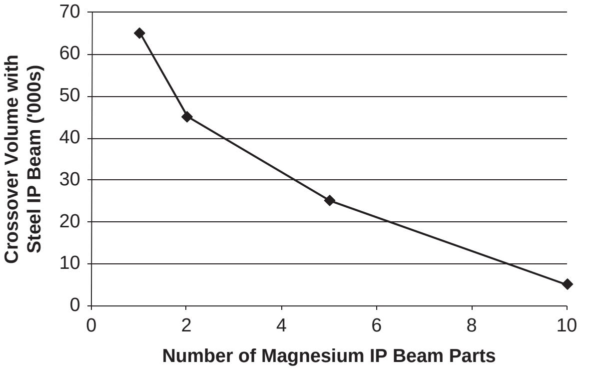

Fig. 10. The effect of magnesium IP beam segmentation on cost parity production volume.

costs. In fact, when considering development costs, the magnesium design was actually modeled to be the lowest cost option over a broad range of material prices and production volumes. When the main structure of the magnesium IP beam was segmented into multiple parts, this cost advantage decreased (and ceased at levels of significant segmentation). These results provide quantitative support for the widely held belief that parts consolidation can reduce costs.

Since these conclusions are based on fundamental characteristics of the two designs and their manufacture, the quantitative specifics of the result are sensitive to key assumptions within the modeling. As Fig. 9 clearly shows, the competitive position of the incumbent steel design is strongly tied to the prevailing material prices. The values reported in this paper were based on a recent historic average price for steel sheet at \$0.81/kg. The past few years have witnessed steel price volatility greater than in any period over the last twenty years. Industry trends would indicate that this volatility is unlikely to persist, causing decision-maker concerns to once again focus on the historically volatile price of magnesium.

It is important to note that while this paper has demonstrated the use of process-based cost modeling to quantify the economic consequence of design and material changes, the analyses presented consider only manufacturing and development economics. The driver for contemplating a switch to magnesium components is their associated weight savings. Regardless of whether this lightweighting is employed to improve fuel economy or vehicle performance, the reduced mass provides some value to the consumer and, by extension, the firm. This value would vary according to vehicle market specifics, but should be considered in a final design decision.

Ultimately, this paper has demonstrated several key issues that have previously been absent in quantitative discussions of materials selection. Firstly, development costs can play a significant role in establishing the economically preferred materials technology. Secondly, this economic impact does not occur uniformly across designs, the production technologies that realize those designs, and, by extension, the materials from which those designs are fashioned. Finally, generative process-based cost models are able to provide quantitative insight into this interdependent set of issues. The nature of case analysis precludes fully generalized conclusions, but the results shown herein suggest the potentially significant role of development costs in the materials selection decision process.

Critically, the models used in this paper are suitable to address these questions early in the design phase, when materials options are still being considered. In the end, the use of tools like the ones described herein should make it possible for designers to consider a broader set of material candidates, facilitating the introduction of novel materials options.

Appendix A. Process-based cost model

As mentioned previously, process-based cost models work backwards from cost. The methodology detailed in this appendix is for the calculation of manufacturing costs; these include the costs of fabrication and assembly. The costs as presented in this work are shown on a per piece basis. The cost elements under consideration include: variable costs—materials, energy, and labor; and fixed costs—main machine and auxiliary equipment, tooling, building space, maintenance, and fixed overhead costs. The total per piece cost for a component or assembly, *i*, is the sum of the cost elements for that component; as shown in Eqs. (A.1)–(A.3).

$$C_{i,Total} = C_{i,Variable} + C_{i,Fixed} \tag{A.1}$$

$$C_{i,Variable} = C_{i,Material} + C_{i,Energy} + C_{i,Labor} \tag{A.2}$$

$$C_{i,Fixed} = C_{i,Equipment} + C_{i,Tooling} + C_{i,Building} + C_{i,Maintenance} + C_{i,Overhead} \tag{A.3}$$

To calculate each of these elements of per piece cost, the annual cost of each element (e.g., tooling cost) is divided by the saleable annual production volume as shown in Eq. (A.4).

$$C_{i,El} = AC_{i,El}/PV_{Saleable} \tag{A.4}$$

where $AC_{i,El}$ is the annualized cost associated with a given element (El) and $PV_{Saleable}$ is the annual production volume of i. The costs for each element are the sum of that element's costs calculated for each stage of a manufacturing process. For example, for a steel stamping operation, costs would be calculated for the blanking operation (stage $j = 1$), and then subsequently for the forming operation (stage $j = 2$). The two sets of costs projections would be combined for the total stamping cost projection. This is shown in Eq. (A.5):

$$C_{i,El} = \sum_{j=1}^{n} C^{j}_{i,El} \tag{A.5}$$

where n is the total number of stages in the process.

Effective production volume is a key variable used to calculate several cost elements. This is the number of gross units that must be produced to yield the desired number of saleable units—$PV_{Saleable}$. If at process stage, j, a certain percentage of production is rejected, x_j, then the effective production volume at stage j, $PV^{j}_{Effective}$, is given by

$$PV^{j}_{Effective} = PV^{j+1}_{Effective}/(1 - x_j) \tag{A.6}$$

For the final stage, that is when $j = n$, $PV^{j+1}_{Effective} = PV_{Saleable}$.

Following this logic, it is possible to estimate the operating volume at the first stage (or for any given stage) in terms of the net desired output, $PV_{Saleable}$. Specifically, for an arbitrary stage k the operating volume follows:

$$PV^{k}_{Effective} = \frac{PV_{Saleable}}{\eta^{k}} = \frac{PV_{Saleable}}{\prod_{k}^{n}(1 - x_j)} \tag{A.7}$$

where $(1-\eta^{k})$ can be thought of as an overall rejection rate from the kth stage on.

A.1. Variable costs

The variable costs for each stage of a production process are projected based on the effective production volume required for that stage, but are allocated according to the net output of the process chain (see Eq. (A.4)). The gross material unit cost at stage j,$C^{j,gross}_{i,Material}$, is calculated using Eq. (A.8).

$$C^{j,gross}_{i,Material} = (Part_{Mass} \times U_{Material})/(1 - Scrap_j) \tag{A.8}$$

where $Part_{Mass}$ is the mass of the part; $U_{Material}$ the unit cost of the material (usually in currency per mass); and $Scrap_j$ the percent of scrap generated by process stage j. For the part fabrication models used in this work, parametric models were constructed to relate part characteristics to expected scrap rate. Based on these definitions, the annual material cost for stage j can be calculated as

$$AC^{j}_{i,Material} = C^{j,gross}_{i,Material} \times PV^{j}_{Effective} \tag{A.9}$$

The energy cost for a process stage is calculated as the product of the energy usage for the equipment at that stage and the unit cost of energy. This is shown in Eq. (A.10):

$$AC^{j}_{i,Energy} = E^{j} \times U_{Energy} \times PV^{j}_{Effective} \tag{A.10}$$

where E^{j} is the energy usage per unit for the machine(s) at stage j and U_{Energy} the unit cost of energy (usually in currency per time · power).

As shown in Eq. (A.11), the labor cost for a process stage is calculated as the product of the number of laborers required for that stage N^{j}_{Labor}, the unit cost of labor U^{j}_{Labor}[4] (usually in currency per unit time) and the amount of total paid labor time required for that stage T^{j}_{Labor}.

$$AC^{j}_{i,Labor} = N^{j}_{Labor} \times U^{j}_{Labor} \times T^{j}_{Labor} \tag{A.11}$$

Total paid labor time, T^{j}_{Labor}, is calculated as shown in Eq. (A.12).

$$T^{j}_{Labor} = \frac{PV^{j}_{Effective} \times CycleTime^{j} \times D^{j}_{Labor}}{\Gamma^{j}_{Labor}} \times APOT \tag{A.12}$$

In the above expression, $CycleTime^{j}$ is the average amount of time required to produce one batch of parts for process stage j; D^{j}_{Labor} the percent of laborer(s) time dedicated to process stage j (between 0 and 1); Γ^{j}_{Labor} is labor efficiency—the ratio of productive working time to total paid time (between 0 and 1); and $APOT$ represents *annual paid operating time* and is calculated as $APOT = DPY \cdot (24\text{–}NS\text{–}UB)$ with symbols defined subsequently for *available line time*.

A.2. Fixed costs

The annual cost for a given fixed cost element is calculated as shown in Eq. (A.13):

$$AC^{j}_{i,El_{Fixed}} = R^{j}_{El} \times LR^{j} \tag{A.13}$$

where R^{j}_{El} represents the annualized equivalent of the investment cost for a given resource and LR^{j} the number of parallel sets of the resource required and allocated to the cost of producing the component of interest.

For a cost projection method to be effective, non-uniform cash flows must be allocated to a specific cost category. In the case of capital equipment costs projected in this work (those fixed cost elements shown in Eq. (A.3), these cash flows are allocated to specific components and process stages according to machine operating time. Given that capital equipment tends to have a usable lifetime greater than one product life cycle, these costs are also modeled as uniformly distributed over the equipment lifetime. To take into account the opportunity cost of having funds invested in capital equipment, a capital recovery factor is used (de Neufville, 1990); the annual allocated cost for a given resource, R^{j}_{El}, for process stage j is shown in Eq. (A.14):

$$R^{j}_{El} = I^{j}_{El}\left[\frac{(d(1+d)^{S_{El}})}{((1+d)^{S_{El}} - 1)}\right] \tag{A.14}$$

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[4] It should be noted that labor rates can differ for various stages of a process (e.g., more skilled labor is required at some stages).

where I^{j}_{El} is the required investment for the fixed cost element for process stage j; d the periodic discount rate; and s_{El} the usable lifetime over which the investment is distributed. The quantities used for these variables in this work are presented in Table 3 (of the main text).

The number of parallel production process lines required and allocated to produce the needed production volume for process stage j, LR^j, is calculated using Eq. (A.15).

$$LR^j = \begin{array}{ll} reqLT^j/availLT^j, & non-dedicated \\ \lceil reqLT^j/availLT^j \rceil, & dedicated \end{array} \tag{A.15}$$

where $availLT^j$ is the available production time for process stage j and $reqLT^j$ represents the time required to produce the necessary quantity of parts for stage j. If a fixed cost is dedicated, LR^j is rounded to the next highest whole number (i.e., the entire yearly cost is attributed to the component even if there is only fractional usage). If the fixed cost is non-dedicated, it is assumed that fixed cost element is shared with some other product; in this case only the fractional usage is attributed to the component. For the purpose of this work, only tooling costs are dedicated; all other fixed cost elements are non-dedicated.

Available production time for process stage j is calculated according to Eq. (A.16).

$$availLT^j = DPY \cdot (24 - NS - UB - PB - UD) \tag{A.16}$$

where DPY is the operating days per year for the design shop, NS the no operations (h/day the plant is closed), UB the unpaid breaks (h/day), PB the paid breaks (h/day), and UD is the unplanned downtime (h/day).

The time required to produce the necessary quantity of parts for stage j, $reqLT^j$, is calculated using Eq. (A.17).

$$reqLT^j = CycleTime^j \times PV^j_{Effective} \tag{A.17}$$

A.3. Assembly model

While the process-based cost model for automotive assembly follows the same principles as that of the fabrication models, there is one main difference. Whereas in the fabrication models additional production capacity is added in parallel, in the assembly model capacity is added in series. The assembly model is driven by the takt time, TT_i, for assembly i. The takt time for assembly i is calculated using Eqs. (A.18) and (A.19), where $availLT_i$ is as defined above and $PV_{i,Effective}$ is calculated using η for the entire assembly process.

$$Rate_i = PV_{i,Effective}/availLT_i \tag{A.18}$$

$$TT_i = Rate_i^{-1} \tag{A.19}$$

The amount of joining time $JT_{i,b}$, required for assembly i and the amount of equipment used is dependent upon the joining method b (e.g., spot welding, riveting, etc.). The amount of joining time and the takt time are used to determine the required amount of equipment $reEQ_{i,b}$ as shown in Eq. (A.20). This is based on the type of equipment and the joining rate.

$$reEQ_{i,b} = JT_{i,b}/TT_i \tag{A.20}$$

The number of stations, v is based on the maximum amount of that type of equipment that can be placed at a station, $mxEQ_b$. This is shown in Eq. (A.21). For assemblies with multiple joining methods, the total number of stations, N_i, is calculated using Eq. (A.22).

$$v_{i,b} = reEQ_{i,b}/mxEQ_b \tag{A.21}$$

$$N_i = \sum_b v_{i,b} \tag{A.22}$$

The investment required is projected based on the number of stations and the amount and type of equipment required. The yearly cost is then calculated using Eq. (A.14).

The calculation of material costs in the assembly model is altered due to the fact that in assembly processes the material is usually some type of consumable. The calculation for annual material usage for assembly i, $AC^{Assm}_{i,Material}$ is calculated in Eq. (A.23):

$$AC^{Assm}_{i,Material} = \sum_M \sum_b U_M \cdot PV_{i,Effective} \cdot \Upsilon_{b,M} \tag{A.23}$$

where U_M is the unit cost of material M and $\Upsilon_{b,M}$ is the material usage per assembly of material M for joining method b. The per assembly cost is calculated as shown above.

Given that the assembly process is driven by takt time as opposed to cycle time, the calculation of labor costs for the assembly model is altered. The annual cost of labor for assembly is calculated using Eqs. (A.24) through (A.26):

$$AC^{Assm}_{i,Labor} = APT^{Dir}_i \cdot U^{Dir}_{Labor} + APT^{IDr}_i \cdot U^{IDr}_{Labor} \tag{A.24}$$

$$APT^{Dir}_i = DPY \cdot (24 - NS - UB) \cdot \sum_b D^{Dir}_{b,Labor} \cdot v_{i,b} \tag{A.25}$$

$$APT^{IDr}_i = DPY \cdot (24 - NS - UB) \cdot \sum_b D^{IDr}_{b,Labor} \cdot v_{i,b} \tag{A.26}$$

where U^{Dir}_{Labor} is the unit cost of a direct laborer and U^{IDr}_{Labor} the unit cost of an indirect laborer; $D^{Dir}_{b,Labor}$ and $D^{IDr}_{b,Labor}$ are the apportioned effort of direct and indirect laborer(s) per station for method b, respectively; and all other variables are as defined above.

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