

The importance of product development cycle time and cost in the development of product families

MICHAEL D. JOHNSON^{a*} and RANDOLPH E. KIRCHAIN^b

^a*Department of Engineering Technology and Industrial Distribution, Texas A&M University, College Station, USA;* ^b*Department of Materials Science & Engineering and Engineering Systems Division, Massachusetts Institute of Technology, Cambridge, USA*

In today's technologically driven world, the importance of innovation and product development is growing. Firms must develop innovative products faster and more efficiently. This has increased the importance of being able to quantify product development performance. This work attempts to quantify development effort and lead-time based on product and project characteristics. The effects of product platforming on development effort and lead-time are analyzed.

To assess the impact of product platforming on development effort and lead-time, models are presented which estimate these quantities based on product and project characteristics. Development cost is then forecast using direct engineering effort with indirect cost. These costs are then compared with fabrication and assembly costs. The effects of product platforming on development lead-time and cost are analyzed. Two case studies are examined: two instrument panel beam families and an automotive body-in-white family.

Results indicate that development costs, while generally a small percentage of total costs, can have significant effects on technology choice and lead to substantial cost savings in product families. Part size and complexity are shown to be the have the most significant influence over development effort. The engineering required for assembly and fabrication are shown to dominate total development costs.

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*Corresponding author. Email: mdjohnson@tamu.edu

Introduction

Development is the set of activities that transform a concept for satisfying perceived needs into a product or service that is ready for the market. Innovative firms use development to increase demand or even create entirely new markets through novel product design. In today's technology driven marketplace, the importance of design and, therefore, development seems unquestioned. This importance is further reinforced because development not only establishes the functional performance of a product, but also drives the economic characteristics of that product. In fact, it is widely cited, that between 70% and 90% of total project costs are determined during the early stages of the development process (Bhimani and Mulder 2001, Shehab and Abdalla 2001). Furthermore, recent research has reinforced the importance of development in the context of other available options for firm spending. Specifically, the return on research and development spending *vis a vis* capital expenditure has been shown to be much more effective at boosting operating margin, market value, and sales growth (Hsieh *et al.* 2003).

Nevertheless, reaping the benefits of effective development often requires a large irrevocable investment. For some complex products, the product development process can take years and require millions of person-hours of effort (Clark and Fujimoto 1991). Accordingly, measures of performance of the development process, such as product development cycle-time, also known as lead-time¹, and engineering effort² are widely applied and tracked. While the importance of product development cycle time on product profitability and success has been well documented (Weston and Simmons 1993, Cohen *et al.* 1996, Gupta and Souder 1998), the engineering effort required for product development has received little attention in the literature. This is true despite evidence showing a positive correlation between engineering effort and development cycle time (Clark *et al.* 1987).

1. Lead-time is the calendar time that passes from concept development to the end of pilot production.

2. Engineering effort refers to the number of engineering hours (often tracked in person-quarters or person-years) that are needed to go from concept development to the end of pilot production.

In contrast to its impact, the cost of development is generally assumed to make up a small portion of the total development effort cost, but this portion is rarely quantified. Recent trends have further raised the importance of development, making the lack of information regarding development costs increasingly unacceptable. In particular, the demands of consumers for product variety have increased considerably in the past and are expected to continue to do so in the future (Pine 1991, Pine 1993). These effects are magnified by the accompanying trend toward decreasing product lifetimes (Schonberger 1987, von Braun 1990, Pine 1993, Uzumeri and Sanderson 1995). In response, firms must develop more and more products that stay in the marketplace for shorter and shorter time periods. In turn, these trends put pressure on development organizations to be more nimble and productive. The use of product platforms and product families has been proposed to help reduce this pressure. A product platform is a set of subsystems from which derivative or variant products can be developed and manufactured (Meyer and Lehnerd 1997). 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 (Gonzalez-Zugasti *et al.* 2000). Platforming has been shown to increase development effort efficiency, and reduce both development time and product cost (Ulrich 1995, Gupta and Souder 1998, Muffatto 1999, Gonzalez-Zugasti *et al.* 2000). Several researchers have highlighted the importance of cost when providing product variety (e.g., Martin and Ishii 1996, Tu *et al.* 2007, Zhang and Tseng 2007). However, few quantitative analyses into the interaction between product platforming and development effort have been performed.

The ability to assess the effects of platforming and product family decisions on product development effort and lead-time can provide important information to decision-makers. As an example, consider a common quandary that confronts designers: while parts commonality can decrease part costs and/or engineering costs, it may constrain future designs and lead to coordination problems (Collier 1981, Clark and Fujimoto 1989, Nobelius and Sundgren 2002). Quantifying the relationship between product platforming decisions and product development performance would allow designers and strategists to make explicit trade-offs in the context of this and other questions that emerge due to the tension between platforming strategy and development process efficiency.

This work presents a process-based model of the product development process that delivers such capability – quantifying the impact of platforming decisions. Specifically, this model examines the impact of platforming on product development effort and lead-time. The costs and lead-time for both standalone products and product families are quantified for two automotive-related cases studies – alternative instrument panel architectures and body structures. Case study results show development costs in the context of total product family cost (including fabrication and assembly). As this paper will demonstrate, knowledge about product development cost and lead-time can have real impact on architectural and technology decisions. The article is organized in the following manner. First, previous literature regarding product development lead-time and engineering effort is summarized to provide the reader with an understanding of previous work regarding the modeling of development performance. Second, a modeling methodology, framework, and outcomes are detailed. Next, case studies are presented that exercise these models. Finally, case study results and model performance are discussed regarding applicability for general development decision-making.

Development Process Modeling

The literature dealing with the evaluation of product development is rather large, and focuses primarily on the lead-time metric. Interestingly, several researchers have also shown the importance of product development lead-time as it relates to project success. This can be from the perspective of development personnel (Rosenau 1988, Rosenau 1989) or from a commercial and financial perspective (Hall and Jackson 1992, Kalyanaram and Urban 1992, Datar *et al.* 1997). In response to this importance, some major companies have even adopted time-to-market as their principal metric of product development projects (Cohen *et al.* 1996).

Given the significance of development lead-time, several researchers have also examined the project characteristics that influence product development lead-time and, from that, deduced methods by which development lead-time could be predicted. One of the earliest attempts to study the development process is Norden's (1960) analysis of the distribution of effort over a period of time for a development project. Organizational characteristic have also been shown to dramatically affect development lead-time. An

example is the scheduling of task overlap, increasing the number of overlapped tasks increases iterations (Roemer *et al.* 2000), and increased iterations have been shown to increase lead-time (Smith and Eppinger 1993). Griffin (1997) observed that cross-functional teams and a formal development process reduce development cycle time. In addition to organizational characteristics, inherent project characteristics have also been shown to affect development lead-time. Clark and Fujimoto (Clark and Fujimoto 1989) found that for the concept and planning phases of the automobile development process, lead-time was dependent on product complexity (as determined by price), body variations, and product innovativeness. Griffin's (1993) work also found that development lead-time was 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. Although there is an abundant amount of research on aggregate development lead-time (i.e., lead-time for the entire product), little work has been done to relate individual development product and project characteristics to lead-times for specific stages of the development process. Griffin's, Clark's, and Fujimoto's work all suggest that this should be possible and that the lead-times could vary significantly.

As mentioned previously, correlations have been found between product development cycle or lead-time and engineering effort (Clark *et al.* 1987). It should be possible then to use product development effort data to estimate development effort lead-time and cost. Adler *et al.* (1995) used 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. Given the large portion of labor costs that make up design projects, engineering effort could also provide a good estimate of design project cost (Bashir and Thomson 2001). Roy *et al.* (2001) studied the relationship between detailed design time and component characteristics. The effects of part geometry on both quantitative, or direct design time, and qualitative, or "thinking" time, were analyzed. 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) (Wallace and Hales 1987), a multiplier would have to be applied to these design time estimations to determine the total cost and lead-time. Smith and Morrow (1999) provide an extensive

review of research that has been carried out looking at the relationship between aggregate product development effort and lead-time and project characteristics. They also point out the importance of models that are rigorous, tractable, and applicable; while there are several rigorous models, there has been a potential loss of applicability. Very little work has been done to relate part and process characteristics to engineering effort and lead-time. Most other models or formulations are highly aggregated, using overall project characteristics to project overall time and/or cost. Finally, a large portion the previous research relies on detailed data not usually available at the beginning of the development process when model output could be used to make explicit trade-offs. This work builds upon previous research to propose a generative modeling method, built around the concepts of process-based cost modeling that can be used to estimate both product development lead-time and cost (derived from engineering effort) based on characteristics of a product and the development process in place at the early stages development. The details of this methodology are presented in the next section.

Modeling Methods: Projecting Development Performance from Product Characteristics

The importance of reliable cost information in the development stage cannot be overstated. In some cases, the decisions made in the early stages of the product development process can lead to and affect billion dollar investments. Given these stakes, uninformed decisions can cause irreparable harm to the firm. Specifically, a number of authors lament that the divorce of the cost estimation process from the design process leads to either cost constraints, which limit designer flexibility, or asynchronous cost estimation and expensive iterative redesign (Noble and Tanchoco 1990, Wei and Egbelu 2000, Field *et al.* 2001); neither of which lead to effective product development outcomes. In light of this, products should be designed with a close eye to both customer preferences and cost.

A valuable cost estimation tool would allow the designer to make explicit trade-offs between product characteristics and their marginal cost. Specifically, Noble and Tanchoco (1990) 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. Such cost estimation tools could then be used to guide decisions during the early stages of the product development process.

Cost modeling attempts to realize such a tool 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 (or analogous) cost estimation uses similarities between a current product or process being studied and previous products or processes that have been completed to project costs; generative (or parametric) cost estimation projects costs based on production requirements and operational conditions (Asiedu and Gu 1998, Weustink *et al.* 2000). The fact that variant-based costing relies on historic products makes it less useful for assessing novel processes, materials, or architectures. Because the specific cases presented deal with some form of novel technology, the model presented in this paper was derived from the perspective of a generative costing method.

Several generative models have been proposed for use in cost estimation of both manufacturing and assembly (Hu and Poli 1997, Jain 1997, Kang 1998, Shehab and Abdalla 2001) and others³. In the end, each of these makes use of cost models to support technology choice decisions. However, in none of these studies were modeling approaches used to comprehensively project the cost of design or development associated with the applications under evaluation.

While no standard method of cost modeling is widely used and accepted, one generative cost modeling approach that satisfies all of the preferred characteristics proposed by Noble and Tanchoco is process-based cost modeling. Process-based cost modeling (PBCM) is an early stage cost estimation tool that has been used to project manufacturing or assembly costs based on part and process characteristics. While PBCM approaches have previously been used to answer numerous research questions related to manufacturing costs (Busch 1987, Han 1994, Jain 1997, Kang 1998, Kelkar 2000), the following sections will demonstrate that these methods can be adapted to forecast engineering effort as well.

3. For a more exhaustive discussion of this topic see Johnson (2004).

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 these 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 fundamental physical relationships and/or through statistical analysis.⁴ A detailed description of PBCM methods is beyond the scope of this article. Interested readers are referred to Busch (1987) or Kirchain and Field (2001) for a full description of the method. For the purposes of this document, those key aspects of constructing a PBCM that are unique for modeling development activities will be detailed.

General Model Framework

The goal of the proposed product development model is to project both the cost and expected lead-time for a development project based on the characteristics of the product and the specific development context. To project development cost, the model comprises four key cost elements – labor, equipment, software, and overhead / supervision – for each phase of the development process. These four cost elements were selected based on feedback from several design managers at an automotive OEM and based on their prevalence as focal issues within the literature.

The allocated cost per assembly variant v , is computed according to Equation (1) to Equation (15). Aggregated costs are calculated as:

$$C_{Total}^v = C_{Labor}^v + C_{Equipment}^v + C_{Software}^v + C_{Overhead}^v \quad (1)$$

$$C_{El}^v = \frac{AC_{El}^v}{PV^v} \quad (2)$$

$$AC_{El}^v = TC_{El}^v \times crf(\text{product life}) \quad (3)$$

4. In the case of the development model, this is limited to statistical analysis, since no fundamental physical relationships were identified to correlate between part and project characteristics and development effort.

where C^v = unit cost (\$ per saleable unit) per assembly variant, v ; AC^v = annual cost (\$), PV^v = annual production volume (saleable assemblies produced), TC^v = total cost over product life, and $crf(\text{product life})$ = capital recovery factor with s = product life as defined in Equation (4); and El = cost element (Labor, Equipment, Software, Overhead).

A key element of any cost forecast is the method used to allocate non-uniform cash flows to appropriate activities, here the development cost of a specific component. For the purposes of this model, all development costs were assumed to occur prior to or near the start of production. As such, even nominally variable cost elements like labor are aggregated, amortized, and allocated to individual products as per Equation (1) through Equation (3). Additionally, in the proposed development cost model, those cash flows with periodicity longer than one year (e.g., equipment investments) are assessed as if distributed uniformly in time over the usable lifetime of the relevant resource. An amount equal to the product of that uniform cost rate and the time that the resource is used by the modeled development activity is assessed to that activity. The opportunity cost associated with tying up funds either for equipment investments specifically or development expenditures in general are incorporated using a standard capital recovery factor (crf) defined as:

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

Where s = number of periods over which is investment is distributed and d = periodic discount rate (here, $d=10\%$) (de Neufville 1990).

In developing these costs for specific variants that are members of a product family, individual components can occur in one of three varieties: 1) Exclusive, components that only exist in that variant; 2) Shared, components that are used without modification in multiple variants in the product family, and 3) Modified, components that are slightly modified variations of those used by other variants in the product family. All costs associated with Exclusive components are allocated to the variant that comprises them. As described below, the cost of shared components are allocated either across variants based on production volume or to the first variant (which contains the component) designed within the family (depending on assessment perspective).

To provide more resolution on the impact of platforming, both cost and lead-time measures were assessed from three distinct perspectives. The first perspective, referred to as the Standalone Cost and Standalone Lead-time, represents the projected cost or lead-time associated with a variant or product family assuming that each variant was produced independently (i.e., without the benefits of component or process sharing). In this case, all components are assumed to be exclusive and no cross-variant allocation of cost is required. The second perspective, the Shared Cost of a variant, quantifies the production volume weighted ratio of that variant's cost contribution to the total cost for a part or assembly. Stated conceptually, the Shared Cost of variant v would be:

$$Shared\ Cost^v = Exclusive\ Development\ Cost^v + Total\ Shared\ Development\ Cost \times \frac{PV^v}{\sum_{platform} PV^w} \quad (5)$$

where $\{platform\}$ represents the set of all variants. The final perspective, the Incremental Cost or Incremental Lead-time of a constituent part or assembly, reveals the extra cost or time that is incurred to produce a variant of that part or assembly, assuming that the investment⁵ for the original parts has already been made. It should be noted that these assessment perspectives can be used for manufacturing costs as well.

Considering the above definitions, the Shared Total Labor Cost is computed based on Equation (6) and Equation (7):

$$TC_{Labor, Shared}^v = wage \times \left(\sum_i TDH_{i,v} + \frac{PV^v \times \sum_w \sum_s TDH_{s,w}}{\sum_w PV^w} \right), \quad \begin{array}{l} \forall i \in \{exclusive^v\}, s \in \{shared^v\} \\ \forall w \in \{platform\} \end{array} \quad (6)$$

$$TDH_{x,w} = \left(reqRTH_{x,w} / designer\ productivity \right) \quad (7)$$

where $\{exclusive^v\}$ is the set of components i , exclusively in variant v ; $\{shared^v\}$ is the set of components within v that are also used in other variants; $TDH_{x,w}$ is the total paid time for designers allocated to the development or modification of component x in variant w (hours); $reqRTH_{x,w}$ is the projected required active computer time to design or modify component x for variant w ; $designer\ productivity$ is defined as the ratio of average total paid time per designer to the average time spent doing design activities; and $wage$ is the

5. This investment could be fixed cost of manufacturing or development cost or time.

average salary for designers (\$/hour). The Standalone Labor Cost can also be computed using Equation (6) and Equation (7). For a Standalone scenario, the set $\{shared^v\}$ is null and the second term with the parentheses in Equation (6) falls out. Incremental costs are computed without any sharing across variants. As such, the Incremental Labor Cost is computed simply as:

$$TC_{Labor,Incremental}^v = wage \times \left(\sum_i TDH_{i,v} \right), \quad \forall i \in \{exclusive^v\} \cup \{shared^v\} \quad (8)$$

Notably, the character of $TDH_{i,v}$ within $\{shared^v\}$ would be expected to differ across the set of variants within the product family. For the first variant, shared design efforts would include developing novel components. For subsequent variants, efforts would be limited to design modifications of previously designed components.

At the assembly level, total Shared Equipment Costs are computed according to Equation (9) through Equation (11):

$$TC_{Equip,Shared}^v = \sum_i \left(Inv_{Equip,i} crf(s_{Equip}) LR_{i,v} \right) + \frac{PV^v \sum_w \sum_s (Inv_{Equip,s,w} crf(s_{Equip}) LR_{s,w})}{\sum_w PV^w}, \quad \forall i \in \{exclusive^v\}, s \in \{shared^v\} \quad (9)$$

$$LR_i = \frac{TDH_i}{availLT} \quad (10)$$

$$availLT = DPY \cdot (24 - NS - UB - PB - UD) \quad (11)$$

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).

As before, Equation (9) can be used without modification to compute total Standalone Equipment Cost. Similarly, total Incremental Equipment Cost is calculated as:

$$TC_{Equip,Incremental}^v = \sum_i \left(Inv_{Equip,i} crf(s_{Equip}) LR_{i,v} \right), \quad \forall i \in \{exclusive^v\} \cup \{shared^v\} \quad (12)$$

Although this study only considered capital costs in the form of equipment, the above formulation is appropriate for extension to other capital costs which are deemed relevant (e.g., facilities).

The total shared cost of software and overhead are treated as in Equation (13) and Equation (15), respectively; total incremental cost of software and overhead are treated as in Equation (14) and Equation (16), respectively

$$TC_{Software,Shared}^v = UC_{Software} \times \left(\sum_i (LR_i) + \frac{PV^v \times \sum_w \sum_s (LR_{s,w})}{\sum_w PV^w} \right) \quad (13)$$

$$TC_{Software,Incremental}^v = UC_{Software} \times \sum_i (LR_i) \quad (14)$$

$$TC_{Overhead,Shared}^v = Oh \times \left(\sum_i (RTH_i) + \frac{PV^v \times \sum_w \sum_s (RTH_{s,w})}{\sum_w PV^w} \right) \quad (15)$$

$$TC_{Overhead,Incremental}^v = Oh \times \sum_i (RTH_i) \quad (16)$$

where $UC_{Software}$ is the unit cost of software licenses per year per seat, Oh represents the ratio of indirect labor costs to direct design labor effort, and set applicability is consistent with all preceding expressions.

The fundamental determinant of all of four cost elements is the projected magnitude of engineering effort (i.e., required active computer time representing the expected person-hours of designer time). As such, to incorporate sensitivity to changes in product or project characteristics within the model, relationships were developed to capture the impact of these on engineering effort. The following section details these relationships, as well as the analytical and data collection methods used to develop them.

The secondary goal of the proposed development model was to project the expected lead-time associated with a specific development effort. The model presented in this paper is similar to that of Alder et al. (1995) in that it views the engineers in the development process as resources that are used to complete tasks. In contrast, the model presented herein estimates the engineering effort required to perform development functions based

on part and assembly characteristics, as opposed to high and low estimates of effort based on previous work. This model also uses empirical data to determine the amount of calendar time required to complete a given amount of engineering effort. This calculation begins by computing the $TDH_{x,w}$ for each component or assembly of each variant for each stage of the development process as detailed above; these *total design hours* figures are summed to determine the overall engineering effort for the variant (or total incremental effort). Given that there are limited resources available for a given development project, the total number of engineers available, TEA_q for that stage, q , for a given project is specified. This is used to determine the total development hours that are allocated to each engineer. However, some components or assemblies in a development stage require a large number of total design hours; engineers working on other components or assemblies could not easily switch to and complete small portions of this work. To accurately convey this, a maximum number of engineers per component or assembly $MEPC_q$ for stage q is also specified.⁶ This is then used to determine which ratio is larger: that of total development hours per total engineers available or that of the maximum development effort required for a given component per the maximum number of engineers per component. This engineering effort density is then divided by *availLT* to determine development lead-time for that stage. This is shown in Equation (17) below, which calculates stage lead-time, ST_q for a single variant:

$$ST_q = \frac{\max\left(\frac{\sum TDH_x}{TEA_q}, \frac{\max(TDH_x)}{MEPC_q}\right)}{availLT} \quad (17)$$

Finally, the amount of overlap between development stages is used to determine overall project lead-time. Total project lead-time, TT , is determined by summing the products of the stage lead-times, ST_q and the overlap factors for those stages, OL_q . The overlap

6. For stages where smaller projects are worked on, such as detailed design this might be a single engineer; for stages where larger projects are the norm, this might be a team of twelve engineers.

factor, OL_q , is the portion of that stage that must be completed before the next stage can commence. This is shown below in Equation (18):

$$TT = \sum_q ST_q \cdot OL_q \quad (18)$$

In the end, as the case studies presented in a later section will demonstrate, this combination of features allows for powerful insights around the impact of development costs in determining the economically preferred technology and architectural strategy for a given product family.

Modeling Engineering Effort across Product Development Stages

The core element of the proposed development model is a set of empirically derived models that relate characteristics of the product under development and the project context to projected engineering effort. Roy et al. (2001) propose that when modeling the development process, that 1) the process should be well understood, 2) dissimilar products should not be mixed, and 3) data for as many designs as possible should be collected. Prevailing wisdom about modeling also dictates that the development process should also be well established and stable. To accommodate these conditions, data on engineering effort was collected at various stages of the development process for projects designing a range parts and subassemblies, specifically automotive structures and closures. At each stage, similar parts and subassemblies were assessed. All data were collected at a single, large automotive OEM. The specific extent and target of data collection is detailed subsequently according to each stage of development. A set of models was then formulated to relate these data to engineering effort. A diagram of the stages in the product development process that was examined is shown in Figure 1.

Insert Figure 1 Here

For the purpose of this work, models of the advanced engineering, prototyping, and process development phases of the product development process were constructed. Within the firm under investigation, the concept development and product planning stages of the development process occur before technology selection decisions. Since the

focus of this inquiry is the impact of cost information on such decisions, these stages were assumed completed, not relevant, and not modeled. The subsequent pilot production and ramp-up phases of the development effort were also not modeled.⁷ The advanced engineering phase of the development process for automotive structures and closures includes two stages: the detailed design of individual parts as well as determining the formability (manufacturability) of these parts. Next, both virtual and physical prototypes are produced for finite element analysis and physical validation. It should be noted that the finite element analysis 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.⁸ The process development phase includes the fabrication engineering required for the individual parts and the engineering required for the assemblies and subassemblies of the body or closure. Activity specific data were collected through half hour face-to-face surveys of engineers in both truck and car divisions.

Advanced Engineering Data

For the advanced engineering phase of development, each engineer was asked to select between two and four (depending on available time) recently completed (released) parts or assemblies of varying size and complexity. In addition to contact information, the engineers were asked to specify how long they had been performing similar engineering work. Engineers were asked to identify the material of the part and the manufacturing technology used to fabricate the part. They were also asked to estimate the geometric complexity of the part based on a five-point scale. The engineer 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. In both stages of the advance-engineering phase, the engineer was asked to estimate the total

7. Both pilot production and ramp-up were excluded from analysis because of their current high degree of variability in terms of effort and duration, even for existing designs and technologies. Project resources precluded analyses of sufficient scope to characterize such high variance activities.

8. The extent of modern physical crashworthiness testing is largely dictated by regulation and is little affected by technological characteristics within the vehicle. New designs frequently incur additional simulation and testing expense, but these costs are almost exclusively attributable to novelty, not to specific technological characteristics.

time spent working on the part in question at the computer. It was specified that the estimate should include all iterations and any work done between reception of the task requirements until the part was released to the next stage. The calendar time or number of days required to complete this amount of work was also queried.

For the detailed design stage, information was also collected about the 1) if the part contributed to the structural integrity and crash-worthiness of the vehicle, 2) amount of time it would take to add features or change the parts overall size, 3) the likelihood of the part having to be changed after an acceptable engineering solution had been reached, 4) the number of iterations which had occurred in design of the part, 5) the amount of overlap in the project (“one” – most tasks done in parallel vs. “five” – most tasks done sequentially), and 6) the sensitivity of this part to changes in other parts (the likelihood that design changes would be required for the part in question if a mating or proximate part changed). For the detailed design stage, twenty-three engineers were surveyed producing fifty-nine responses.

In addition to the general advanced engineering phase questions, for the formability engineering stage, engineers were asked about 1) the amount of computer processing time required for an analysis, 2) if the part was a surface part (i.e., seen by the consumer), and 3) the number of formability analyses done (iterations to acceptable performance). Formability engineers were also asked about the novelty of the manufacturing process being employed. For the formability stage, six engineers were surveyed producing twenty-four responses.

Prototyping Data

For the prototyping phase, engineers were asked to select recent projects that they had completed.⁹ They were then asked about entire projects as well as individual tests or procedures. 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 the range of manufacturing technologies reported. In the finite element

9. It should be noted that these are aggregated projects, done only on major assemblies.

analysis (FEA) stage, the engineers were asked to estimate the amount of effort required to set up their analyses. This time included the effort required to mesh the models received from design engineering, 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. Similar to the FEA engineers, physical validation 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. Finally, all prototyping 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 during prototyping. This was due to the aggregated nature of the systems under consideration as well as the standardization of the analyses. Fifteen FEA engineers were surveyed producing information about eight auto bodies and eleven enclosures. Seven physical validation engineers were surveyed produced data for four bodies and seven closures.

Process Development Data

The process development phase included the engineering for the fabrication of individual parts as well as assembly engineering. Unlike the previous phases of the development process, larger groups performed these sets of tasks. For stampings (the most widely used forming technology in the automotive industry), part characteristics and the corresponding person-hours and calendar time for several parts were 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 selection 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. Similar to the advance engineering phase, data about the size and complexity of the parts was tabulated. 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. 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 manufacturability, machine selection, process design, and tooling design for parts of varying complexity and size. These experts were interviewed and data were collected for die-casting, tube hydroforming, roll forming, and both tube and stretch bending. For steel stamping, data were collected from two managers yielding information for thirteen parts.

For the assembly engineering stage, engineering managers were asked to provide data for recently completed projects. Again, assembly engineering is a set of tasks performed by a larger group. First they 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 which would join a similar length so that a consistent metric could be used. The number of distinct joining methods and number of parts in the assembly were also recorded. These engineering managers 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 engineering managers provided data regarding seventeen subassemblies.

General Product Development Data

In addition to data about direct engineering effort, for each development stage, data were collected about indirect costs from engineers and engineering managers: 1) overhead, 2) computer hardware and software, and 3) physical prototypes. These data were combined with development resource requirements to estimate development cost as described previously.

Engineering Effort Model Outcomes

As previously mentioned, linear regression analysis was used to relate part and assembly characteristics to engineering effort. While all stages were rigorously analyzed, detailed results for the formability engineering stage are presented here along with a summary of the other analyses performed. Due to the highly proprietary nature of these data, all engineering effort and calendar time quantities were normalized by the mean of the data set. All cost data are also disguised. All trends shown are consistent and proportional to those found using actual data.

Data gathered from six engineers about the formability of twenty-four parts was analyzed. Table 1 shows the Pearson correlation matrix for the formability survey data; statistically significant ($p \leq 0.1$) relationships are detailed as follows. As expected, the time required to perform a formability analysis was positively correlated with part complexity, part size, and whether or not the part is a surface part. It is expected that larger more complicated parts would require longer analysis time. It is also reasonable that the higher quality required for surface parts would lead to greater effort. Part complexity and part size were positively correlated. While it is possible to have small complex parts or large simple parts, large parts tend to contain more features and are therefore more likely to be complex. The size of a part was also positively correlated with whether or not the part was a surface part. These correlations were then used to select variables for use in the multiple linear regression analyses.

Insert Table 1 Here

Four linear correlation models were evaluated for the engineering time required to perform a formability analysis. These models are shown in Table 2. Model one included part size, part complexity, and whether the part was a surface part. Notably, the coefficient for surface status was not statistically significant, excluding it from further consideration. Model two incorporates part complexity and size. Models three and four included a single variable each: part complexity and size, respectively. Neither models three or four have a R^2 as high as model two. Given the higher R^2 and its use of 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 is shown in Figure 2. A plot of standardized residuals verses modeled values for model two is shown in Figure 3. This figure shows the error terms to be evenly distributed and mostly

independent of the predicted value. These results were then combined with data about indirect costs and formability engineers' efficiency to determine engineering effort and subsequently cost. Data collected regarding the correlation between engineering effort required and calendar time was then used to estimate the cycle time for the formability engineering stage.

Insert Table 2 Here

Insert Figure 2 Here

Insert Figure 3 Here

In addition to formability engineering, other stages of the development process were analyzed in a manner similar to that presented. Table 3 shows a breakdown of the data used to predict engineering effort for these other stages. To determine the major part and project characteristics that affect computer design time a model that contained part size and the amount of overlap in the project was used. To determine the amount of time required to make overall length and width changes, part size was used. The engineering effort required for the capital portion of fabrication (for stamping) engineering used a model based on part size and complexity. The model for assembly engineering used subassembly complexity and the number of parts in the subassembly. As previously mentioned, the aggregated and standardized nature of both the finite element analyses and physical validation stages did not allow for statistical analyses. Data for the individual tasks and completed projects were compared to standardized task lists and found to be consistent (i.e., within 20% with no statistical bias) with projected effort. This data along with that collected about the cost of physical prototypes was used to complete the proposed development model. Overlap factors, the percentage of a proceeding task that must be completed prior to the subsequent task beginning, similar to those found in product development planning documents at the automotive OEM were used in the development lead-time calculations. The model is demonstrated in the context of two case studies in the following section.

Insert Table 3 Here

Exercising the development model: two case studies in body structure platforming

To assess the importance of development cost in the context of total product cost and determine the suitability of process-based cost modeling as a technique for determining development cost and lead-time, two case studies are presented. Process-based cost models are used to forecast development, parts production, and assembly costs (details of the production and assembly models can be found in Johnson and Kirchain (2006)). Total costs for producing product variants individually and as a planned product family are investigated. Although the models allow for exploration of production under a range of strategic and operational conditions, all results are presented here for the conditions shown in Table 4.

Insert Table 4 Here

Case one: alternative instrumental panel beam designs

The first case examines two alternative instrument panel (IP) beam designs: 1) a tube-based steel design¹⁰ and 2) a die-cast magnesium design which affords significant parts consolidation. The steel IP beam (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. In addition to parts consolidation, the magnesium design is attractive because it affords significant weight savings (approximately 14%) over the steel design. The development costs forecast using the proposed development model are shown in Figure 4. In both cases, development costs are dominated by fabrication and assembly engineering; accounting for over 90% of development costs in the both designs.

Insert Figure 4 Here

Interestingly, although the complex die-casting (i.e., the primary structured part within the Mg IP design) is projected to demand more than three times the development effort than the analogous steel structure (i.e., the steel tube), the development cost for the overall magnesium design is much less. In aggregate, total development costs for the Steel IP were over six times higher than those of the whole Mg IP. This difference was driven primarily by savings in Assembly

10. Most vehicles today use similar tube-based steel instrument panel beams.

Engineering and Fabrication Engineering. In both cases, higher Steel IP costs derive from the larger number of parts and more complex assembly process required for the steel design.

To quantify the impact which development costs plays in a technology choice decision, both designs were also modeled for parts production and assembly cost. As shown in Figure 5, these manufacturing costs are distributed differently for the two designs. The magnesium design incurs significantly higher fabrication costs – due to the high unit cost of magnesium— but has much lower assembly costs – due to the extent of parts consolidation. At the production volume shown (75,000 units per year), the steel design provides marginally lower direct manufacturing costs. Notably, at this production volume, the development savings are sufficient to drive the total cost of the magnesium IP design to only slightly more than the cost of the steel design (see Figure 5). In fact, the inclusion of development costs makes the magnesium design more competitive at all production volumes and the least cost option across a broader range of conditions (Johnson and Kirchain 2006).

Insert Figure 5 Here

To assess the role of platform design strategies on development lead-time and cost, a permutation of the above case study was examined in which each of two IP designs were shared across two vehicles. The second vehicle was assumed to require an IP beam design variant that was 10% longer than the original design (required for a vehicle with a larger track or width). Related to this, some authors have noted that the ability to share parts between variant products is often limited by more integrated designs (Ulrich 1995, Muffatto 1999). For the purpose of this case, the two magnesium design variants were assumed to share the pair of unique brackets, but not the main magnesium structure. The steel variants were assumed to share a large portion of the brackets (those whose spacing was not significantly affected by the length change) and a portion of the tubular structure. The Standalone (Var 1) and Incremental (Var 2) development costs for the two alternative designs are shown in Figure 6. Based on these assumptions, the Incremental Development Costs for the second steel variant were 86% less than its standalone costs (\$1.17 for the Incremental Costs vs. \$8.49 for the Standalone Costs). The Shared Development Costs for the two steel variants were 43% lower than the Standalone Costs (\$9.66 in the shared case vs. \$16.98 for the two standalone steel beams). The Incremental Development Costs for the second magnesium variant were 79% lower than the Standalone Costs (\$0.28 for

the Incremental Costs vs. \$1.32 for the Standalone Costs); Shared Development Costs for the magnesium variants were 40% lower (\$1.60 in the shared case vs. \$2.65 for the two standalone magnesium beams).

Insert Figure 6 Here

In addition to development cost, development lead-time was also analyzed. As mentioned previously, overlap factors similar to those found at a major automotive OEM were used to project development lead time. Formability was assumed to begin after 50% of the detailed design stage was completed; fabrication engineering stage was assumed to begin after 100% of formability stage was completed; the assembly engineering stage was assumed to begin after 10% of the fabrication engineering stage was completed. Figure 7 shows the projected Standalone Lead-times for the first variants (Var 1), and the Incremental Lead-times for the second variants (Var 2), of both the steel and magnesium designs. The Standalone Lead-time for the original steel IP beam (shown as equal to one time unit for Steel Var 1 in Figure 6) was projected by the model to be over 250% longer than that of the standalone magnesium beam. This difference was due mainly to the increase in assembly engineering lead-time required to integrate the numerous components within the steel design. As would be expected, Incremental Development Lead-times (IDLt) for the variant designs were projected to be dramatically lower than for the original designs. The IDLt for the Mg IP beam decreased from 0.37 for the original design (Mag Var 1) to 0.25 for the variant (Inc. Mag Var 2), a reduction of 32%. Interestingly, the IDLt for the steel IP was projected to drop even more dramatically, falling by 80% to 0.20 time units, over 20% shorter than that of the second magnesium variant. The difference in these two results occurs because while the time-consuming detailed design of the main magnesium castings must be replicated across variants, the steel design can leverage many existing components, allowing the latter to greatly reduce lead-time for subsequent variants. As a result, while the steel design has longer Standalone Development Lead-time, variants off the original steel IP beam design can be developed more quickly than variants off the original magnesium IP beam design.

In the end, the proposed development model provides information about development cost and lead-time that may alter the design decisions surrounding the instrumental panel case. For the production assumptions presented for the case (most notably operating at a production volume of

75,000 units per year), the model projects a difference in development costs that is sufficient to show the magnesium design as a much more cost competitive option than when considering part production and assembly costs alone. In fact, including development cost and using base-case conditions, the cost parity point between the two designs shifts from 10,000 units per year to 70,000 units per year. Obviously, access to predictive models about the performance and cost of development activities can have an influential impact on the materials and process selection decisions. The addition of development cost activities also had a marked effect in the case of the platformed instrument panel beams. The costs of development activities accounted for 20% and 3% of total standalone costs for the Steel IP and Mg IP designs, respectively. However, the cost savings associated with development activities as a result of part sharing accounted for 36% of total cost savings in the case of the Steel IP design and 16% in the case of the Mg IP design.

Insert Figure 7 Here

Case two: body structures

The second case investigates the significance of platforming strategy to the cost of producing a family of vehicle bodies-in-white (BIWs). Specifically, a family of mid-sized vehicles structures comprising BIWs for a convertible, a sedan, and a crossover (the emergent class of vehicles combining features of SUVs and passenger cars). All three variants utilize a tubular steel, spaceframe-type construction. Although this architecture is not widely applied in high-volume production, it offers attractive characteristics for lower volume niche applications. Furthermore, the tubular design affords much greater opportunity for parts commonality. This product family was designed to capitalize on that characteristic and share a large number of parts. Summary information about the three designs can be found in Table 5. When considered as a whole the three designs share 46% of all parts produced.

Insert Table 5 Here

As with the previous case, the proposed development model was used to forecast development costs for the three variants. Figure 8 shows the breakdown of these for the three variants. Both Incremental and Standalone Costs are presented. Standalone Costs assume that only that variant is developed, while Incremental Costs assume the convertible is produced first then the sedan and then the crossover (each bar represents only the additional development effort needed given

that the designs share components and subassemblies). No bar is plotted for the Incremental Cost of developing the convertible as it is assumed to be the original design.

Notably, in Case Two no specific alternative technology was explored. However, as will be quantified, this case further emphasizes the potential significance of development costs in establishing the cost effectiveness of platforming strategies. Across all three variants, fabrication and assembly engineering made up a majority of the development costs, together accounting for around 80% of the costs in each case. As with the IP beam case, parts sharing led to significant savings in development cost. For both the sedan and crossover designs, Incremental Development Costs were projected to be more than 40% lower than the corresponding Standalone Development Cost. Furthermore, examining the full set of three vehicles, the model projects a total cost decrease of 28% compared to developing all components independently. Not surprisingly, savings in fabrication and assembly engineering made up most (90%) of the forecast development cost savings. These savings are directly linked to avoided costs associated with part and subassembly commonality.

Insert Figure 8 Here

As a second test of the importance of development cost in technology decision making, development costs were combined with modeled costs of part production and assembly for the three body designs. These costs were derived using the proposed models of part production and body construction were used to project corresponding manufacturing costs. Figure 9 shows these costs for producing 75,000 units per year under two scenarios: the sedan being produced independently (Standalone) and all three variants are produced in concert sharing investments where possible (Shared). Notably, the shared strategy reduces total cost by 8%.

While development accounts for only 7% of the total (i.e., development, fabrication, and assembly) cost, almost 30% of the total cost savings are due to the reduction in development cost resulting from parts and assembly sharing (as seen in Figure 9). So, while development cost may not be a large contributor to aggregate costs, it can become a determinant factor in decisions involving platforming and product families. Ignorance of the magnitude of these potential savings could lead to inferior product family development strategies.

Insert Figure 9 Here

Discussion

The significance of effective development for technologically driven products is rarely questioned. Innovative development can increase demand by realizing enhanced products, driving down operating costs, or even creating new markets. However, these benefits come with real costs. Development activities require expensive, skilled resources, which must be engaged through numerous, often iterative activities. Aware of this, many successful firms closely monitor their development activities, tracking both the use of development resources (engineering effort) and the elapsed time that is required to go from concept to salable production (lead-time). Nonetheless, despite their importance as performance metrics, the specific correlation between product characteristics and engineering effort and/or lead-time has not been extensively studied.

This work has presented a methodology for studying that relationship as well as a corresponding model, which has been built through a detailed study of engineering practices within the automotive industry. These analyses of engineering practices have repeatedly showed that component size and complexity are the strongest drivers for development cost throughout its many stages. Generally, this trend would dissuade the adoption of integrated designs, which are inherently larger and more complex than any single modular component that they replace. However, as shown explicitly in the first case study, sufficiently integrated designs can provide such significant reductions in assembly and, therefore, the design of assembly processes as to overcome this disincentive. One driving reason behind the lesser attention paid to development costs, is that they are often overshadowed by manufacturing costs for high volume production (as both case studies reveal). Interestingly, however, in both cases, development costs play a key role in establishing the preferred technological option. When considering the IP beam designs, assembly cost savings are *insufficient* to motivate using the magnesium design at production volume of 10,000 per year or greater (considering only cost). However, the associated savings that would emerge from designing both fewer parts and fewer assembly processes are more than adequate to overcome that deficit. In fact, including development cost and using base-case conditions, the cost parity point between the two designs shifts from 10,000 units per year to over 70,000 units per year.

The modeling approach presented in this paper also projected that development cost can play a significant role in motivating the use of product platforms. Similar to integration, product families reduce cost by eliminating unnecessary fixed investments. As redundant manufacturing investments – tooling and equipment – go away, so do the development investments associated with those same activities – fabrication and assembly engineering. For product families, savings can extend to even more development activities, for example, eliminating unnecessary testing and qualification of duplicate parts and assemblies. These trends were shown explicitly in the two cases. The elimination of redundant development activities resulting from part sharing in the product families generated development cost savings well in excess of the development portion of total cost. Such savings can play a critical role in motivating technology choice for low production volume applications, if tools like the one presented in this paper are made available to appropriate decision-makers.

Ultimately, the costs associated with development activities may seem small compared to the investments made in manufacture and assembly, especially for large complex products. However, both as a controllable cost and amplifier of other more recognized strategic benefits, development cost can play an influential role in dictating the lowest total cost technological option. The case studies presented have shown how applying the process-based modeling approach can quantify that role in decisions involving material, process, and architectural decisions. Application of these methods to firm specific contexts should afford product development decision-makers the information that they need to make more economically effective decisions on both product architecture and the production technologies used to realize that architecture.

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Figure 1. Stages of the product development process included in the analyses presented herein

Table 1. 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<0.1

**p<0.05

Table 2. Linear regression models of formability data (standard errors are represented in parentheses).

Model	Constant	Size (dm³)	Part Complexity	Surface Part (1=yes)	R²	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

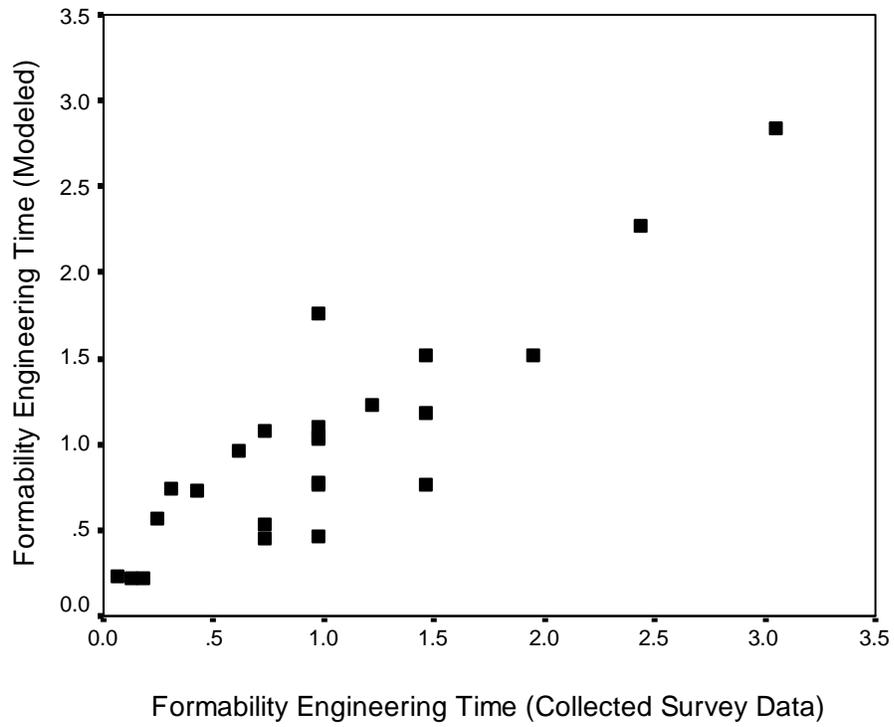


Figure 2. Modeled and collected data for formability engineering time

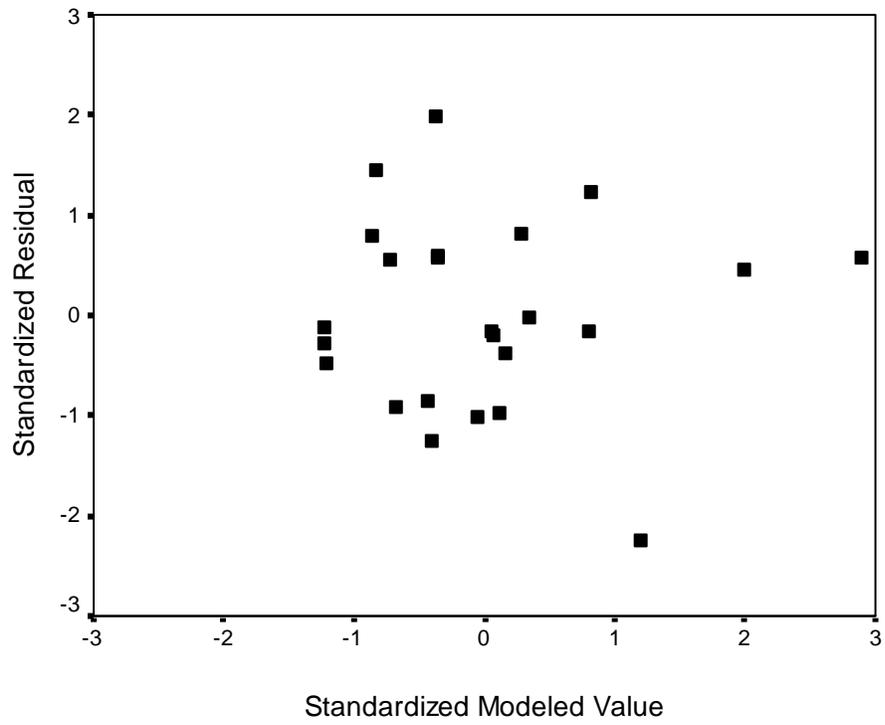


Figure 3. Standardized residuals vs. standardized predicted values for formability engineering time.

Table 3. Summary of multiple linear regression analyses for various development stages (standard errors are represented in parentheses).

	Intercept	Size (dm³)	Complexity	Project Overlap	No. of Parts	R²	F-Stat
Design - Main	0.230	0.002	--	-0.031	--	0.47	17.3
	(0.050)	(0.000)	--	(0.018)	--		
Design - Change	0.114	0.005	--	--	--	0.82	104
	(0.125)	(0.000)	--	--	--		
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)	--	--		
Assembly¹	--	--	0.119	--	0.070	0.88	65.4
	--	--	(0.053)	--	(0.016)		

¹R² for assembly linear regression should not be compared to those which have intercepts.

Table 4. Base model parameters.

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
Interest	0.1	
Equipment Life	15	yr
Indirect workers / Direct Worker (part fabrication)	0.25	
Indirect workers / Line (part fabrication)	1	
Building Unit Cost	1200	\$/sqm
Product Life	5	yrs
Building Life	40	yrs
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

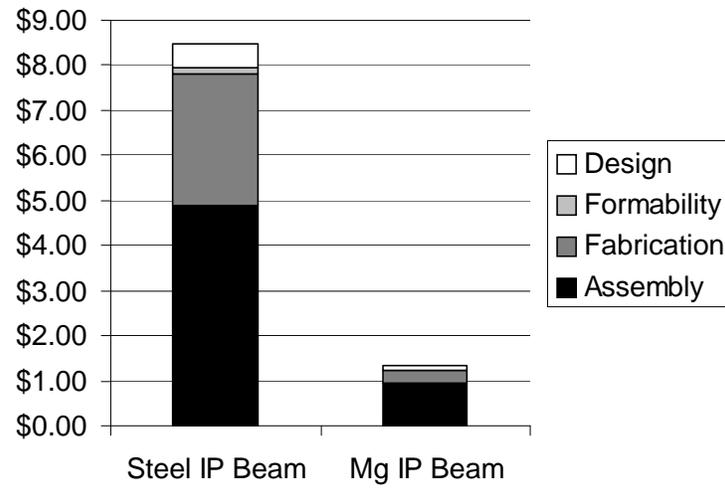


Figure 4. Development costs for IP beam design alternatives.

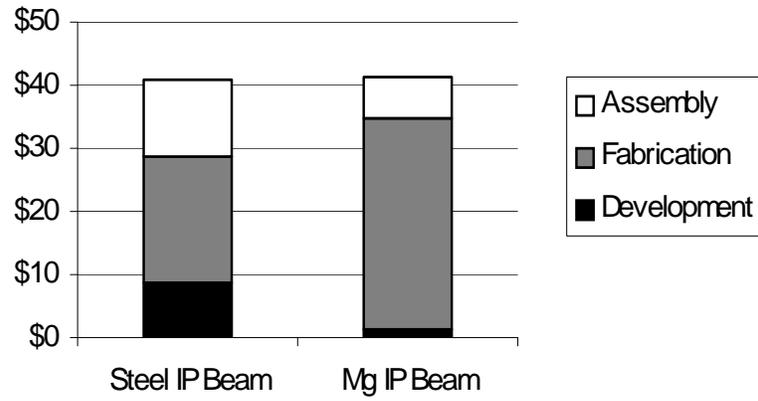


Figure 5. Total costs for IP beam design alternatives.

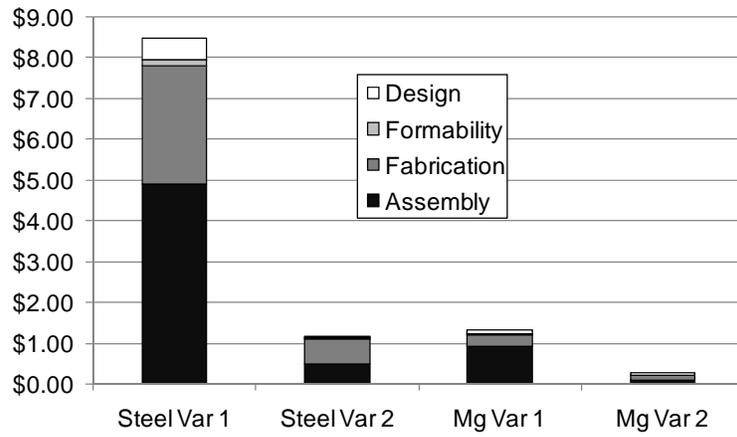


Figure 6. Standalone (Var 1) and incremental costs (Var 2) for IP beam design alternatives.

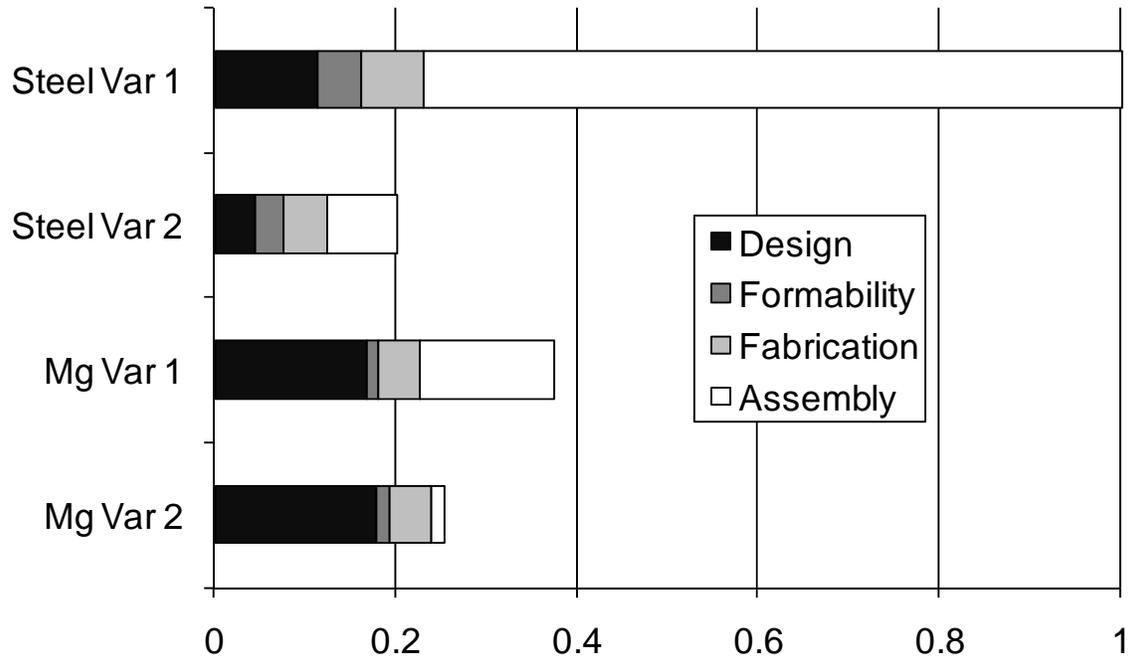


Figure 7. Standalone and Incremental development lead-times for IP beam design alternatives.

Table 5. Tubular design summary.

Manufacturing Process	Total Part Weight (kg)	# of Parts
Casting	48.6	10
Press Breaking	7.9	5
Roll Forming	73.2	16
Resin Transfer Molding	4.5	1
Sheet Hydroforming	13.2	2
SMC	11.7	4
Steel Stamping*	180.5	116
Tube Bending	79.1	25
Tube Hydroforming	6.9	3
Total	425.55	182

***Includes 90 Small parts**

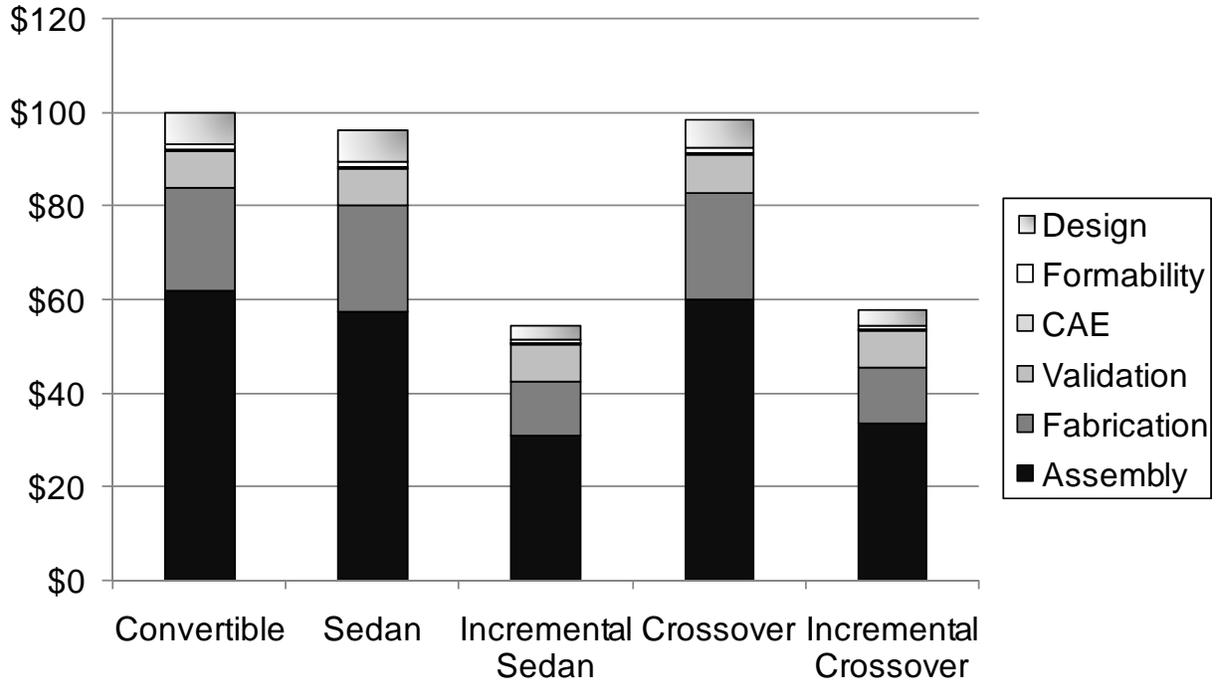


Figure 8. Standalone and Incremental Development Costs for the tubular design.

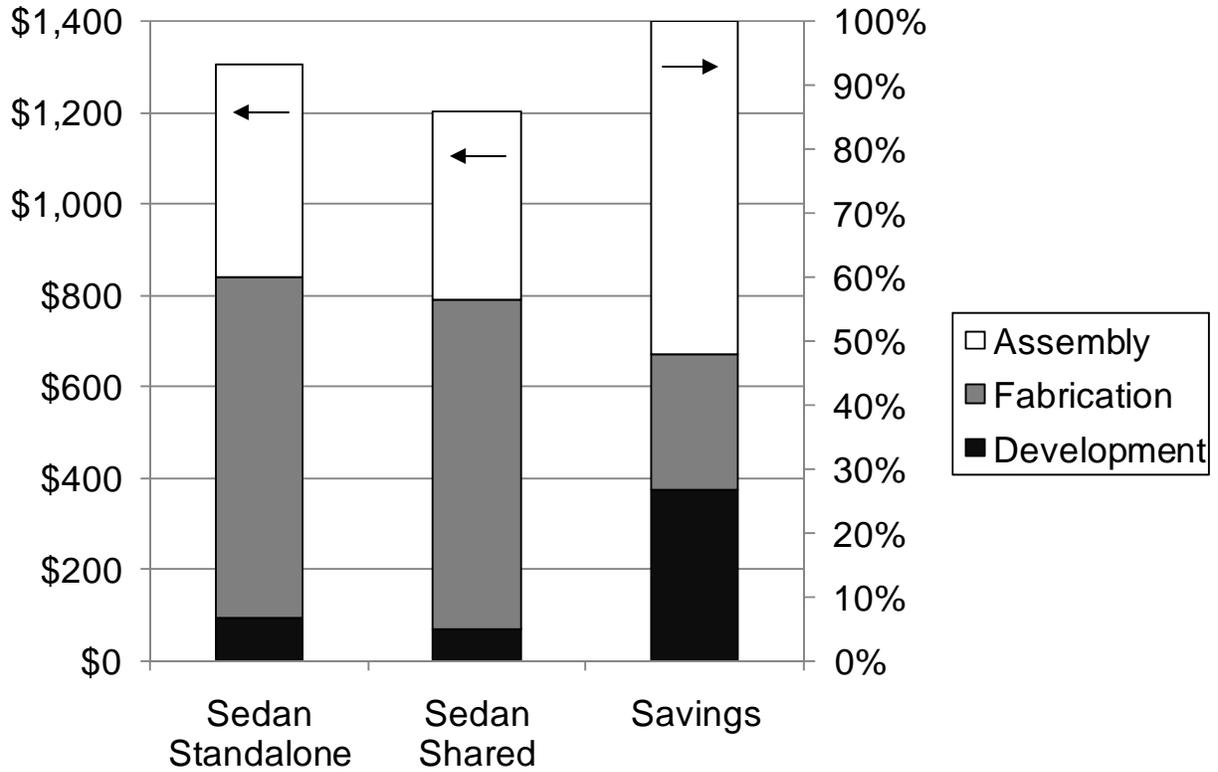


Figure 9. Standalone and Shared Costs for Sedan bodies with cost savings breakdown.