Journal of Mechanical Design. Received April 24, 2018;
Accepted manuscript posted November 09, 2018. doi:10.1115/1.4041943

Is More Less? Benefits and Costs of High-Variety Production in Non-Assembled Manufacturing

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ABSTRACT

While many studies have characterized the costs of product variety in assembly production, there is little research detailing the sources and costs of increased product variety on a non-assembled (fabrication) production line, despite non-assembled products accounting for over 50% of U.S. manufacturing. Our research examines the production-level costs, benefits, and margins associated with producing a variety of non-assembled products, and how design attributes affect these outcomes. We propose a theoretical framework of non-assembled product variety, identifying five general design attributes of non-assembled products that influence product-variety outcomes, and identify potential sources of variety costs and benefits. We then conduct a case study of a plant that produces a large variety of unique products in a single year. We develop a new Process Based Cost Modeling technique to capture the impacts of product variety. Leveraging design of experiments, we model fourteen representative products, altering the mix of products to focus on each design attribute. In our case study, which has relatively large lot sizes, less customized designs, and less flexible equipment, we find that cost increases related to changeovers between product designs are small relative to cost benefits derived from sharing equipment and labor. We provide a framework illustrating how these results generalize to other contexts, which shows that changeover costs will dominate sharing benefits in environments with more customized designs, produced in smaller lot sizes, and processed on flexible equipment.

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1 Introduction

Firms use product variety to increase revenue and access new market segments [1]. However, producing diverse products on a single line comes with drawbacks, including increases in equipment, labor, and fixture and tooling costs, as well as quality issues [2]. Much of the existing research focuses on measurements and methods related to quantifying variety in assembled products and their shared sub-components and modules [3–10]. Non-assembled products (monolithic, fabricated products) lack sub-components and modules to share, making it difficult to apply much of the existing literature to non-assembly environments. Examples of non-assembled products include extruded metal beams, injection molded polymer parts, stamped metal components, additively manufactured components, monolithically fabricated semiconductor dies, and other monolithically fabricated pieces for automotive, aerospace, agriculture, health, defense, and a wide variety of other applications. Furthermore, non-assembled products comprise an estimated 50% of U.S. manufacturing [11]. Our study aims to address this gap in the literature by proposing a theory of non-assembled product variety and quantifying the costs and benefits of producing a variety of non-assembled products on a single line.

We propose a framework of the design attributes that drive product variety costs in a non-assembled production plant and how possible benefits might be achieved. Our theory proposes five general product design attributes we believe to be potential sources of variety in non-assembled products. We then relate these variety attributes to their impacts on production, costs, and benefits. We apply our framework to a case study of a single plant that produces a wide variety of non-assembled products. Using design of experiments (DOE), we select two different samples of products from the plant′s portfolio. The first DOE sample focuses on the facility′s high volume products, the second on products with more extreme product attributes, representing the full product-design space for the plant. We model the production cost of producing these products together using Process Based Cost Modeling (PBCM), a bottom-up technical cost modeling technique that relates design and variety decisions to production costs.

We examine several outputs: shared costs (the cost if products are produced together on the same line), standalone costs (cost of products produced on their own line), changeover costs (the costs of switching between products at a process step) and benefits (cost savings) of spreading equipment and labor costs across multiple products. We find that given the production volumes in the case study, each design attribute accrues benefits attributed to sharing process steps on the line, and changeover costs are low. We find that product attributes relating to treatment and size largely drive benefits associated with product variety. Finally, we examine margins (sales price less production cost) and find that reducing low weight and high treatment ”extreme” products may increase margins.

Our results contribute to two broad insights about non-assembled product variety. First, our results indicate that benefits and costs of non-assembled variety exist along a spectrum, with changeover costs dominating in environments with small lot sizes, and perfect equipment utilization and shared benefits dominating in environments with large lot sizes and equipment dedication. Second, we find that even if perfect equipment utilization is not possible, improving equipment flexibility on a high-variety production line may still garner sizable cost benefits.

2 Background: Product Variety

Research has tied increasing product offerings to increases in revenues and firm profits [12, 13]. Increasing product offerings can in certain cases reduce manufacturing costs due to increased sharing of investments and economies of scale and scope [14–16]. At the same time, increased variety can lead to additional complexities and costs [17]. Indeed, a wide array of operations research demonstrates impacts of product variety, including increased labor requirements, decreased productivity, rework and quality issues, thereby increasing both direct and indirect costs [2, 18–20]. Within this context, much literature has been dedicated to mechanisms to reduce the costs of product variety in the context of assembled products. Many papers focus on designing product families around common platforms [14, 21–23] that have a consistent set of components, systems,

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interfaces, processes, and even knowledge around which derivative products can be built [14, 16, 24, 25]. As non-assembled products are monolithically fabricated and have no sub-components, existing product variety measures focused on sub-components and modules are not useful for explaining the causes and effects of cost changes due to non-assembled product variety [3–7].

Some existing research [14, 21, 23, 24, 26] focusing on the use of common assets and knowledge, scale-related product design, and shared resources may be useful to consider for non-assembled products, as they do not explicitly focus on the modules, interfaces, and sub-components which make up assembled products. Common assets may reduce the risk of adding new, diverse products and improve flexibility [14]; scale-related product platform planning may enable technical efficiencies, minimizing product diversity while still covering the requisite performance characteristics required to serve the market [21, 23, 24]. Additional research quantifies the standalone cost of producing individual products in a family without accounting for shared components, and compares that cost with the cost of a product accounting for component sharing within the family [26]. Another study focuses on platform efficiency and the importance of shared processes and systems in non-assembled production specifically [27].

Non-assembled production refers to fabrication of a single monolithic part, completely integrated, with no sub-components. Assembled production, by contrast, produces a product by joining a number of smaller components through a variety of methods, such as welding, adhesives, fastening, wirebonding, etc. [28–32]. The processes comprising non-assembled production (hereafter referred to as non-assembly processes) fall into categories such as forming (e.g. pressing, stamping, forging, sintering, brazing), subtractive processes (e.g. grinding, milling, turning, photolithography, etching), additive processes (direct metal laser sintering, electron beam melting, metal oxide chemical vapor deposition), phase change processes (e.g., casting, injection molding), and structure-change processes (e.g., coating, heat treatment, surface hardening, polishing) [28]. These products are typically very capital intensive with long life cycles and centralized production, and use raw materials as inputs [33]. Variety in non-assembled products (hereafter referred to as non-assembled product variety) can be achieved through varying product attributes such as material type, geometry, size, and tolerances that influence product performance or demand [33, 34]. Any change in the design of the product is likely to also affect that product′s production process, and in a diverse production line, it is likely design changes to one product will also affect the cost to produce others on the line [35], which we refer to as shared costs. For instance, a design change may require new, unique tooling that requires additional time to change between products [36], which may incur not only time loss, but also product loss while the tooling is calibrated.

Existing product variety literature focuses on assembly-related product attributes such as shared product platforms, components, and interfaces [14, 16, 24, 25]. This is the first paper to examine the shared costs and benefits of non-assembled product variety. As non-assembled products comprise over 50% of all U.S. manufacturing based on dollar value of shipments [11], our work seeks to extend the theory and methods of product variety to this important category of products.

3 Proposed Theory

We propose a theory to examine the relationships between variety in non-assembled product attributes and production cost. Drawing on a review of non-assembled product literature in addition to experience observing various production lines (over 100 hours), and presenting the proposed relationships to several experts of different manufacturing processes for feedback, we develop a general two-part framework to relate non-assembled product attributes to their impacts on the production process. While this framework is suitable for various batched non-assembled processes, including those that fall under the broad categories listed above (forming, mass-change, etc.), this theory may not apply well to vat (chemical or pharmaceutical) and continuous (glass, oil refining) processes and other raw materials.

3.1 Framework: Shared Costs and Benefits

Increasing product diversity on the line poses inherent complexities that increase costs, but may also lead to benefits related to economies of scope (EOS) that decrease costs. Economies of scope can capture know how, learning, information, physical assets, and set up costs [37]. In this paper we focus on the fixed inputs of labor and equipment (capital). As seen in Tab. 1, we separate the effects of sharing diverse products on a single line into two categories: negative effects related to changing between products on the line and positive effects related to EOS.

Changeover costs in non-assembled production are directly related to the impacts of switching from one product to another on the line, and are likely to arise from fixture, tooling, and material changes, in addition to yield losses due to re-calibration or material contamination between cycles.

Conversely, EOS may produce benefits that reduce costs. EOS, defined as "where it is less costly to combine two or more product lines in one firm than to produce them separately" [38], offer benefits to firms in addition to those garnered by increased production volume (economies of scale). We capture the benefits of increased production volume with scope, all else being equal (Tab. 1). If the process step is dedicated (may only be used by the products on that line), the full cost of the process for the entire year is allocated to the products on that line. Adding new products that share processes on a dedicated line increases machine utilization, in turn reducing new equipment required to accommodate unique products and unlocking shared benefits. If products cannot share equipment on the line, or if the equipment (or labor) cannot be used for other purposes within the plant when it is not being used for the product mix on the line (i.e., the equipment or labor is dedicated), the cost of the mix increases.

3.2 Variety in Product Attributes

Because non-assembled products are primarily process based, changes in product attributes directly impact the production process, and increased attribute variety may create new process needs on the line. We identify five attributes that can describe the variety of non-assembled products: size, geometry, material, treatment, and tolerance. Table 2 examines the relationship between increasing variety in each of these attributes to the resulting impact on the production process. Relationships marked with a (+) indicate a positive relationship (for instance, increasing product size variety leads to an increase in fixtures and tooling). Relationships marked with a (-) indicate a negative relationship (e.g., increasing geometric variety may lead to a reduction in yield). However, the (+) and (-) indicate that an increasing or decreasing relationship may exist depending on the type of product and the production process, not necessarily that the relationship will always exist. In this section, we elaborate on our proposed theory of non-assembled product variety.

Increasing the diversity of product sizes on the line has several impacts on the production process. Changes to product size may require process changes and investment [39]; this may include adding equipment (or more expensive equipment) to accommodate new sizes, and batch processes may require increased cycle times and altered batch sizes to account for diverse sizes. For instance, if the size of a fabricated metal piece exceeds the work envelope of a CNC mill, a larger mill may need to be purchased. Similarly, if a heat treatment oven is used for diverse-sized products, a longer cycle time may be needed for a larger products, and all products may need to adhere to the longest cycle time in the batch. New sizes may require new fixtures and tooling and additional time to load, unload, and setup equipment between sizes.

Like size diversity, increasing geometric diversity may require additional tooling and load/unload time, in addition to yield loss to account for adjustments after tooling changes. For instance, if a die is changed to accommodate a larger product size in a plastic stamping process, the first few products may need to be discarded if the die needs to be adjusted. Increased geometric diversity is also likely to affect both batch size (both increasing and decreasing) in addition to possibly increasing cycle times, setup times, and fixtures and tooling price [40]. For instance, when placing diverse products together in a coating cycle, it is possible that the diversity of size may enable more capacity to be filled if the shapes are compatible. Alternatively, batch diversity may require additional space between products (and more cycle time) to ensure a coating uniformly coats

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Table 1. Proposed major shared cost categories within non-assembled manufacturing

Category	Variables	Relationship to Cost
Changeover	Switching Yield Loss	Increase
	Switching Time Loss	Increase
EOS	Machine Utilization: Sharing, Non-Dedication	Decrease
	Labor: Non-Dedication	Decrease

all products. Changing out fixtures and tooling may increase setup time and decrease yield (due to re-calibration, as in the plastic stamping example).

Increasing material diversity may increase scrap due to various material types requiring more or less machining or shaping based on material properties; moreover, additional material loss may accrue due to machine cleaning between production lots [41]. Equipment may require new fixtures and tooling to accommodate different material properties, requiring additional load, unload, or setup times as well as causing calibration- or contamination-related yield loss. For instance, if changing out a material on a process like injection molding, it is likely the die will need to be cleaned, and it is possible the first few pieces may need to be discarded to ensure they are not contaminated with the previous material. The firm may need to purchase material-specific equipment to accommodate unique material properties or to avoid contamination. Batch sizes may also decrease as unique material properties may not be able to be combined in a single batch, thereby increasing costs. Cycle times may need to be increased for similar reasons, increasing costs.

Given the inflexible nature typical of non-assembled production, increasing the variety of treatment steps (machining, shaping, finishing, etc.) would likely require additional equipment, tooling, and fixtures purchases [33]. Increased yield loss is likely to occur as more treatments are added to processes, resulting in more rejected pieces at each step. Finally, increased treatment diversity, even at a single process step, may require additional setup time, both at that step and possible previous treatment steps. This may be seen in the case of etching and deposition in semiconductors; unique etching patterns may require time to setup between, and may also necessitate alternative deposition treatments prior, adding additional setup time.

Increasing the tolerance diversity could require new equipment to accommodate different tolerances. Batch sizes may decrease, as a single batch may not accommodate diverse tolerances. Increased tolerance diversity may increase time required between lots to change fixtures and tooling, as well as possibly increase inspections [42], which may also contribute to increased yield loss due to adjustments after fixture/tooling changes.

3.3 Relationship Between Attributes and Shared Costs and Benefits

We relate the design attributes defined above to their respective likely impacts on shared costs and EOS in Tab. 3. Through our review of non-assembled product literature [28, 33, 39, 42] and our production observations, we expect most of the attributes could decrease EOS (by requiring additional unique equipment or specialized labor), but may also increase EOS (if no additional unique equipment or labor is required). The exception to this trend is geometry, which is likely to only cause tooling change, and unlikely to require unique equipment or labor (resulting in reduced costs related to EOS). It is possible that different attributes may cause these specializations in different industries; for example, in some chemical, food, or pharmaceutical production, cross-contamination concerns may prevent different materials from sharing equipment, making material an attribute that drives specialization. In the case of high-precision products, a narrower tolerance requirement may force firms to invest in higher-precision equipment. However, if equipment can be shared, each of these may improve EOS. For changeover costs, it is likely increasing variety in each attribute increases changeover costs, requiring changes in fixtures

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Table 2. Proposed relationships between variety in selected non-assembled product attributes

Product Attribute	Equipment Price/Quantity	Batch Size	Fixtures/Tooling	Cycle Time	Yield	Scrap	Material Price	Load/Unload/Setup
Size	+	+/-	+	+	-			+
Geometry		+/-	+	+	-			+
Material	+	-	+	+	-	+	+/-	+
Treatment	+		+		-			+
Tolerance	+	-	+		-			+

Table 3. Proposed possible relationships between variety attributes and shared costs and benefits

Attribute	Costs Related to EOS	Costs Related to Changeovers
Size	+/-	+
Geometry	-	+
Material	+/-	+
Treatment	+/-	+
Tolerance	+/-	+

and tooling and producing additional product loss from re-calibration.

4 Data Collection for Case Study

We apply our proposed theoretical framework to a case study of a single plant in a domestic firm. The case study plant produces a high variety of small parts (the exact part cannot be described for confidentiality reasons) via a complex, multi-step manufacturing process. These parts are then sold to industrial manufacturing businesses, where they are used for a period of hours to months and then replaced. This work focuses on the variety and production processes at one of the firm′s domestic plants with high throughput and a broad spectrum of product variety. The focus plant has a total annual production volume (APV) of between 20 and 30 million parts with over 8,000 unique designs. The firm produces parts in small lots ranging from 200-2,000 parts. The firm plans their production schedule daily, adjusting throughput based on longer-term targets as well as daily orders.

4.1 Data Collection

We collected data through the firm′s production management system, observations and interviews with operators, operational managers, plant managers, and production engineers on over 40 equipment types and 20 inputs per equipment type. Additional information, including the input types gathered, are included in Supplemental Material (SM) Section A [INSERT LINK TO SUPPLEMENTAL MATERIAL HERE]. In addition, we collected information on each part′s process and part-specific inputs, gathered from the firm′s production information management system to better approximate cycle times unique to the exact design. For each product, unique process flows are comprised of individual process steps ranging

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Table 4. Major process categories at the focus firm′s production line.

Forming	Consolidation	Shaping	Coating
Forming 1	Consolidation 1	Shaping	Coat A
Forming 2	Consolidation 2	Grinding	Coat B
Forming 3		Surface Treatment	
		Polishing	
		Inspection	
		Washing	

from 5-20 steps each, with some steps, such as washing and inspection, sometimes repeated. We interviewed operators to gather data on additional time required and yield loss incurred by changing between each product on a single equipment type.

The focus firm′s production processes may broadly be split into four major categories: forming, consolidation, shaping, and coating. Forming molds the substrate material into the near-net shape of the product. Consolidation solidifies the substrate material into a solid piece. Shaping refines the geometry, tolerance, and finish of the product. Two types of coating deposit additional coatings on the substrate material. Each of these broad processes may be performed using different pieces of equipment, introducing additional process variety. Broadly, all products begin at forming and go through consolidation, after which different product types go through unique flows of different shaping and coating processes.

Finally, we obtained product price information for the products in the case study. We obtained price data by sales volume for one year, from which we obtained a high price, low price, and sales weighted average. This data is used to understand which products and mixes produce a positive margin and which may incur net cost to the firm.

5 Methods

Drawing on our proposed theory, we examine the relationship between identified product attributes and costs in our case study manufacturing plant. We first select the product attributes that are most relevant to our selected products. Next, we use design of experiments (DOE) to select two different samples of products to capture a narrower high-volume design space and a broader design space in the firm′s portfolio. We then generate costs of the DOE-selected products in various production mixes using PBCM. We use "heat maps" to examine each mix′s shared benefits and major factor inputs by process step. We then examine the margins associated with both individual products as well as product mixes. To understand the impacts of manufacturing flexibility on cost, we compare the costs of producing a high-variety mix with varying degrees of equipment flexibility. Finally, we find the range of lot sizes at which the costs associated with variety outweigh the benefits in a high-variety mix.

5.1 Plant Observations and Variety Attribute Selection

Drawing on our proposed theory, we select four of the identified design attributes that influence product-variety costs to examine in our target facility: material, size, treatment, and geometry (Tab. 5). We measure material diversity as material price per kilogram, and ensure each products material-related inputs are unique to its process to capture differences between materials of similar prices. We use weight as a proxy for size; larger sized parts may require tooling changes or longer processing times, or may lead to smaller batch sizes. We measure product geometry as the number of edges per product; for instance, a square part would have four edges on the top and four edges on the bottom of the part for a total of eight edges,

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Table 5. Selected attributes for case study and their respective measures

Design Attribute	Measure	Units
Material	Material Price	$/kg
Size	Weight	Normalized
Treatment	Treatment Steps (Post-Consolidation)	Quantity
Geometry	Edges	Number of edges

each of which could require work such as shaping or grinding. Finally, since each product goes through the same first broad steps of preparation, forming, and consolidation, we use number of treatment steps after consolidation to capture products with both low and high degrees of processing. We omit the tolerance attribute from our case study because it does not vary widely across products in the portfolio and is determined by size and geometry.

5.2 Design of Experiments

We use design of experiments (DOE) to systematically select products from the design space defined by the chosen product attributes that influence variety costs. Each DOE lays out the products and their related attributes needed to produce results that are non-confounded [43]. The DOEs allow us to test the relationship between the outputs of the PBCM and product attributes, all else considered equal [43].

In this study, we use two DOEs: one capturing six high-volume products (a narrower design space), and another with eight products from an expanded design space, capturing broader ranges of our four selected parameters of variety. We use fractional factorial designs to select enough products to examine the bounds of each selected attribute over two levels, high and low. As data collection and modeling for each additional product is very costly (requiring interviews with several operators and part-specific data collection), we selected fractional factorial designs that would both alleviate concerns about confounding between our variety parameters and also require less data collection.

The two product sets and their maximum attribute ranges are captured in Tables 6 and 7 (the experimental designs may be found in SM Section B). Reported weights are normalized to protect confidentiality; however, the weights of the products would generally be measured in grams rather than kilograms. For each attribute range, the percent capture of production volume is listed. We eliminated geometry as a variety parameter for the high-volume DOE given that a high percentage of products have the same number of edges (eight). As such, the high-volume DOE tests three design attributes, whereas the extreme DOE tests four. The high-volume DOE is also a three-quarter foldover design [44], enabling us to test for confounding between material and weight; tests for these interactions showed low confounding between the attributes.

We selected the products that were closest to our selected DOE given the availability of products in the firm′s portfolio. While we selected the closest product to the DOE-specified attributes, some selections are not ideal. Specifically, the number of treatment steps (post-consolidation) in product two of the extreme DOE is closer to the lowest values of the ”high” treatment values than desired. Product four of the extreme DOE does not adhere to the desired material price level (it is (-), but should be (+)). Product four also has lower than ideal weight. We perform a series of robustness checks (SM Section B), comparing the results with and without these ”weak corners” and modifying the product mixes where appropriate to ensure results are not caused by the non-compliant products in the DOE. We note where robust results are used in the analysis.

5.3 Process Based Cost Modeling

We use PBCM to compare production costs of unique product mixes on the line. PBCM is a bottom-up cost modeling technique that examines cost as it relates to product and process design decisions [45, 46]. PBCM is made up of inputs, a

Table 6. Maximum range, volume captured by high-volume DOE

Attribute Measure	Highest (+) Value	Lowest (-) Value	% Volume Capture
Mat. Pr	44.18	37.9	93
Weight	.13	.02	65
Treat. (Post-Consolidation)	10	4	57
Edges	8	8	72

Table 7. Maximum range, volume captured by extreme DOE

Attribute Measure	Highest (+) Value	Lowest (-) Value	% Volume Capture
Mat. Pr	78.9	37.9	98
Weight	1	.02	92
Treat. (Post-Consolidation)	10	3	67
Edges	12	8	77

model architecture (arrangement of the model), and the mathematical decision rules which simulate the production process, resulting in an annual cost of "good" (throughput less rejects from quality control) products per year. The decision rules are based on those developed in [47], and are listed in SM Section C.

We use plant observations, our informal interviews with plant managers and operators, firm operations databases, and publicly available data to collect the necessary inputs, listed in Tab. 4 (additional information on these processes is included in SM Section A). We collect inputs for a range of best and worst case scenarios to capture various uncertainties and changes that may occur under different conditions (also noted in SM Section A). We then use these ranges to capture uncertainty in the process and variation across products.

We add two new capabilities to our PBCM from prior literature: the use of multiple lots (thereby incorporating the sequencing schedule of products on the line), and product changeover impacts (in the form of additional time and product loss) between lots of different products (documented in SM Section C). These additions enable us to examine various product mixes and their relative costs. By incorporating a product mix, we simulate production of multiple products with different processes on the line at once, enabling different products to share equipment and resources across each other. The additional changeover decision rules increase the changeover time and part loss when changing between two products at a specific process step, allowing us to examine the potential costs and benefits we propose in our theory.

5.4 Product Mix Analyses

Using our DOE selections and the PBCM, we model various annual product mixes, isolating the effects of product-variety costs due to each design attribute. We run two mix simulations for each attribute in the DOEs: one contains only products at the (-) level of the attribute, while the other contains only products at the (+) level of the attribute. Finally, we run one mix combining all levels (i.e., all of that DOEs products together, (+) and (-)). We model our product mixes on an ideal schedule that occurs over the course of approximately one day in lot sizes of 1,000 products, repeating to reach a selected APV of 25 million. We find the optimal production schedule for each mix by minimizing changeover-related material loss for each product mix. Since each mix is run on a dedicated line, the costs associated with changeover-related material losses

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are significantly greater than the costs associated with changeover-related time losses. As such, we find the material loss associated with each changeover, multiplying the yield lost with the material usage of the product. We then use exhaustive iteration to find the optimal order of products in each mix minimizing material loss. Within each mix, we seek to keep the production volume of each product as close to even as possible while still adhering to a 1,000 part lot size. We assume that both machines and labor are dedicated, since operators do not necessarily have the skills to work at different process steps than their assigned process step, and the equipment cannot be used for any other purposes or product types in the facility.

We examine annual mix costs to help us understand which attributes are driving mix cost. To examine changeover costs exclusively, we run the model for each mix with the changeover costs overridden to equal zero. We then subtract the resulting no-changeover mix cost from each full mix cost to find the annual changeover cost for each mix. To understand the impact of flexible equipment within process steps, we unify equipment type across each individual process step for all products in the All mix of the extreme DOE. We include details on this analysis and results in SM Section D.

To calculate shared benefits, we use the model to find the standalone cost of producing each part at the mix-specified volume on its own line. We then sum the standalone values for all parts in the mix. This sum equals a ”standalone” value we would expect the mix to have if each product was produced on an individual line. We then compare these values to the cost of producing them concurrently on one line, labeling the difference between the two as ”shared benefits/costs”. The following equation represents shared benefits/costs for each product mix: $Shared\ Benefits = Total\ Cost - Standalone\ Cost$.

5.5 Heat Maps: Process-Specific Benefits Analysis

We examine each mix′s respective benefits by process type, using heat maps to compare process-level benefits with their key shared-cost related inputs (equipment price and fraction of labor [the number of operators required to operate the equipment]). These maps enable us to look for relationships between each DOE attribute level (+ or -), their process-level benefits, and inputs to help understand which attributes are driving benefits.

5.6 Margins

To estimate the firm′s profit margin, we use price data obtained from the firm. Since the firm alters the sales price of the product for different customers and sales volumes, we use a high and low range of the various sales prices of the product for a single year. With this, we find the margin for individual products as: $Margin = Sales\ Price - Production\ Cost$.

We find a high and low range of margins using the highest and lowest sales price listed for each product. We calculate margins for mixes by multiplying the volume of each respective product in the mix by its sales weighted price. To incorporate uncertainty in production cost, we include best- and worst-case margins by incorporating the best- and worst-case production costs for each product and mix. Uncertainty in production cost is due to measurement uncertainty in addition to variation in human operating and physical operating conditions, and variation in production given the variability of the firm′s production line.

Our profit-margin analysis assumes consumers do not substitute between products (i.e., if one product design is cut from the line, the consumer would purchase it from another firm rather than switching to another product design). While we could not estimate a demand model to confirm this assumption because of a lack of market data, interviews with the firm indicate that this is a reasonable approximation.

5.7 Lot Size

As we note in the Proposed Theory section, we expect variety to incur both costs and benefits. In this case study, costs change with lot volume, with lots requiring proportionately more material, setup and changeover time per lot as lot volume decreases. As such, we find the lot volume range at which benefits begin to outweigh costs (and vice versa). We maintain the optimized schedule explained previously.

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5.8 Sensitivity Analyses

To understand how product mix benefits change under different circumstances, we perform two additional analyses. First, we examine how shared benefits change over a range of APVs. Second, for each product mix, we re-assess the sharing benefits when the products have labor dedication (unused person-hours in a shift must still be paid for), equipment dedication, neither labor nor equipment dedication, and when both are dedicated. We compare these mix costs to their respective standalone costs with the corresponding labor and equipment dedication to examine the shared benefits in each dedication scenario. We include these results in SM Section E.

6 Results

We evaluate various attribute mixes using the PBCM, evaluating the changeover costs and shared benefits for each variety attribute of our high-volume and extreme DOEs. We then investigate the margins associated with the variety attribute mixes, the cost savings associated with flexible equipment, and the lot sizes at which shared benefits are outweighed by changeover costs. All results listed are normalized by a uniform factor protect the firm′s confidential information.

6.1 Changeover Costs

Figure 1 shows the total annual cost related to changeovers between product designs at all process steps. These costs may arise from additional processing time and yield loss due to changing between different product designs at a process step. While the mixes vary in total changeover cost, they are all low compared to their total annual mix cost (accounting for less than 1% of the mix cost). The exception to this is the extreme DOE weight(-), which has a relatively high changeover cost associated with it. The additional volume and time required to accommodate the changeovers in this mix increases the number of forming lines required by one machine. The additional cost of this additional line is several hundred thousand dollars. Without the cost of the additional line, changeover costs would be reduced to several thousand dollars. While this outcome is specific to this particular case, changeover costs are generally low compared to shared benefits; we do not expect this case-specific result will influence the results presented below. Additional discussion of product mix total costs and product unit costs are included in SM Section F. We include robustness checks for weak DOE corners in SM Section B.

6.2 Cost Benefits of Product Variety

Next, we examine the net shared benefits related to the attribute mixes (Fig. 2). Shared benefits are represented as negative numbers, indicating a cost reduction due to EOS; these net benefits also include the changeover costs (positive values) listed above. Evaluating these benefits, we see the highest cost reductions in both the high-volume and extreme DOEs when producing diverse design attributes together (e.g., the +/- product mix containing all products). Weight(-) in both DOEs and treatment(+) in the extreme DOE each exhibit markedly higher net benefits than their opposite attribute level. Both of the DOEs exhibit similar trends between the (+) and (-) levels for each attribute, except for material price, which shows a slight reduction of net benefits going from material(+) to material(-) in the high-volume DOE and a slight increase of net benefits going from material(+) to material(-) in the extreme DOE. In these cases, the shared benefits here are significant; the firm may save millions of dollars per year.

It is worth noting that the individual products in the mix approach minimum efficient plant size[1] between 2-6M APV; we perform a sensitivity analysis to determine how benefits change at different volumes in SM Section E. SM Section G contains additional information on unit cost curves.

[1]Minimum efficient plant size here refers to the point at which product unit costs asymptote as equipment becomes fully utilized [48]. In this case, at MEPS we no longer observe dramatic cost reductions with increasing production volumes.

Journal of Mechanical Design. Received April 24, 2018;
Accepted manuscript posted November 09, 2018. doi:10.1115/1.4041943

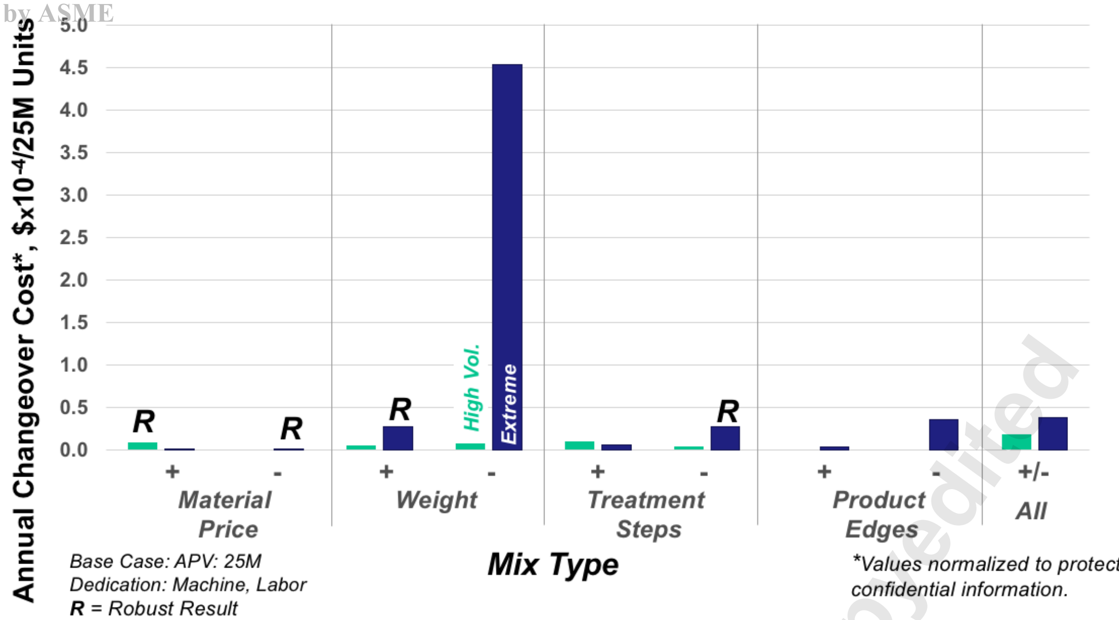

Fig. 1. Changeover costs are low (less than 1% of total annual mix costs), and are greater in the mix that includes both (+) and (-) attributes than for any individual attribute except for the extreme DOE weight(-), which exhibits costs associated from requiring a new line to accommodate the volume and time additions required due to changeovers. Note that the high volume material(+) and extreme material(-), weight(+), and treatment steps(-) results shown are the robust results.

6.3 Process-Specific Benefits Analyses

We use heat maps to extend our analysis, identifying which of our product attribute mixes share more processes and thus accrue more shared benefits. We examine which processes accrue benefits in each attribute mix in order to find relationships between attributes and process; all heat maps may be found in SM Section H. We find that treatment(+) is associated with higher equipment prices in both DOEs, as each treatment(+) mix uses more (and more diverse) process steps than treatment(-) . Furthermore, we find that treatment(+) mixes can share more high-priced and high-labor process steps. This implies that even if a product requires more treatment steps, if the equipment is already in use, and can be shared across products, adding the product may not substantially increase cost.

We find that in the extreme DOE, the weight(+) attribute is associated with less process sharing and higher labor in the forming step, and the weight(-) products associated with much more process sharing in the shaping and coating steps. This may be in part due to the firm′s equipment requirements for heavy products; several extreme weight(+) products are produced with a specific piece of forming equipment that requires constant operator attention because more automated equipment cannot easily handle the heavy products. Finally, the edges(+) mix does not appear to have significant differences in shared benefits in the (+) or (-) attributes.

In the high-volume DOE, we find material(+) associated with greater sharing in several high-labor and high-equipment price steps, including forming, grinding and shaping. In the extreme DOE, sharing for material(+) is greatest in coating, whereas material(-) exhibits greatest sharing in forming and shaping, both of which have moderate-to-high equipment prices and labor needs.

Generally, we find that labor-intensive and high-priced processes both show the greatest benefits from sharing. The heat maps also confirm that broadly, where mixes are able to share equipment and process steps, they achieve cost reductions. While products using the same high-priced equipment incur savings when produced together, even products produced with lower-priced equipment may still incur significant labor savings from being run with other products, particularly if the lower-priced equipment has a high fraction of labor (as with some forming and shaping steps).

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Accepted manuscript posted November 09, 2018. doi:10.1115/1.4041943

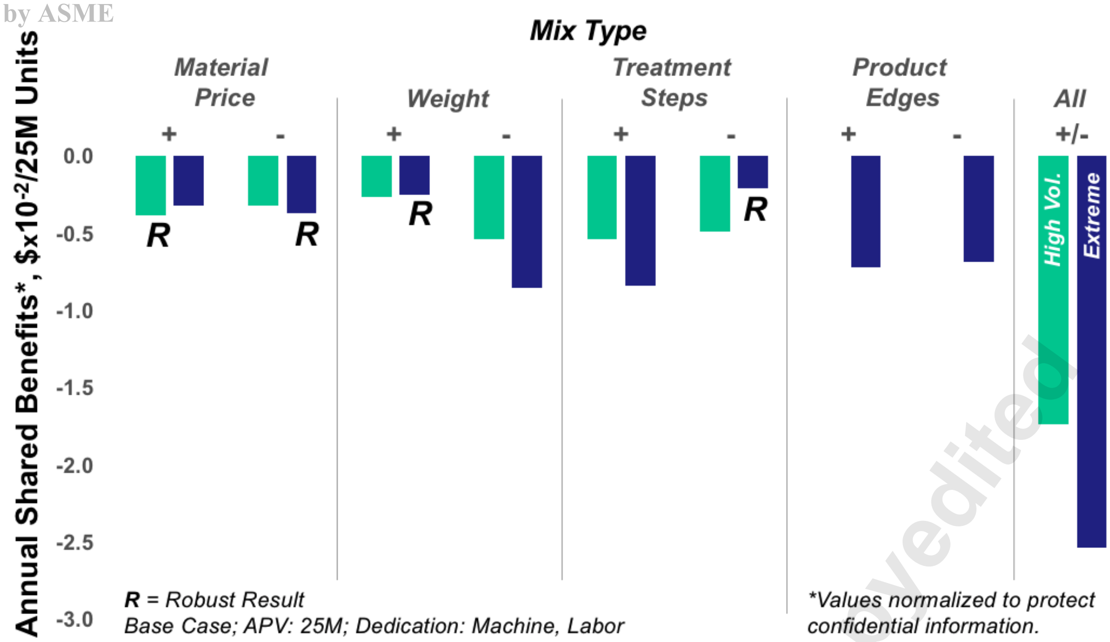

Fig. 2. There are benefits that come from producing diverse product attributes together on the same line. This negative number also includes the *positive* value (cost) of any changeovers associated with each mix. Even with included changeover costs, the benefits derived from producing both (+) and (-) products together on the line are great. The high volume material(+) and extreme material(-), weight(+), and treatment steps(-) results shown are the robust results.

6.4 Margins

The analyses to this point help us understand which mixes are accruing benefits from product variety. However, these mixes may not all exhibit positive profit margins. As such, we calculate the margin for each mix (Fig. 3). Generally, in the range of high and low prices obtained from the firm, the margins for each mix are profitable. However, after incorporating uncertainty in production cost, we find that several attribute mixes do not necessarily exhibit strictly positive margins. Figure 3 shows three attributes which, under lowest-price and highest-cost conditions, do not provide net positive margins: weight(-) and treatment(+) in both DOEs (though the trend is particularly marked in the extreme DOE), and material(+) in the high-volume DOE. All other attributes have a net positive margin. Product-level margins are included in SM Section F.

To investigate the effect of changes in the product mix, we eliminate specific low-margin products from each DOE′s all (+/-) mix and re-calculate the mix margins. With material(+) removed, the high-volume DOE′s high-variety mix margin increases, with a higher possible best-case scenario and a slightly higher worst-case scenario (Fig. 4). We remove weight(-) and treatment(+) from the extreme all(+/-) mix. The revised extreme all(+/-) mix shows a slightly lower best-case margin, with a much higher worst-case margin (Fig. 4).

6.5 Shared Costs and Benefits: Changes by Lot Size

We explore the implications of lot sizes to understand where the costs incurred due to changeovers outweigh the shared benefits associated with both DOEs′ high-variety mixes. We find that costs outweigh benefits between 5 and 10 parts/lot (additional information may be found in SM Section I). In this range, the costs associated with additional changeover time and lost product outweigh the benefits of sharing equipment, labor, and other resources.

Journal of Mechanical Design. Received April 24, 2018;
Accepted manuscript posted November 09, 2018. doi:10.1115/1.4041943

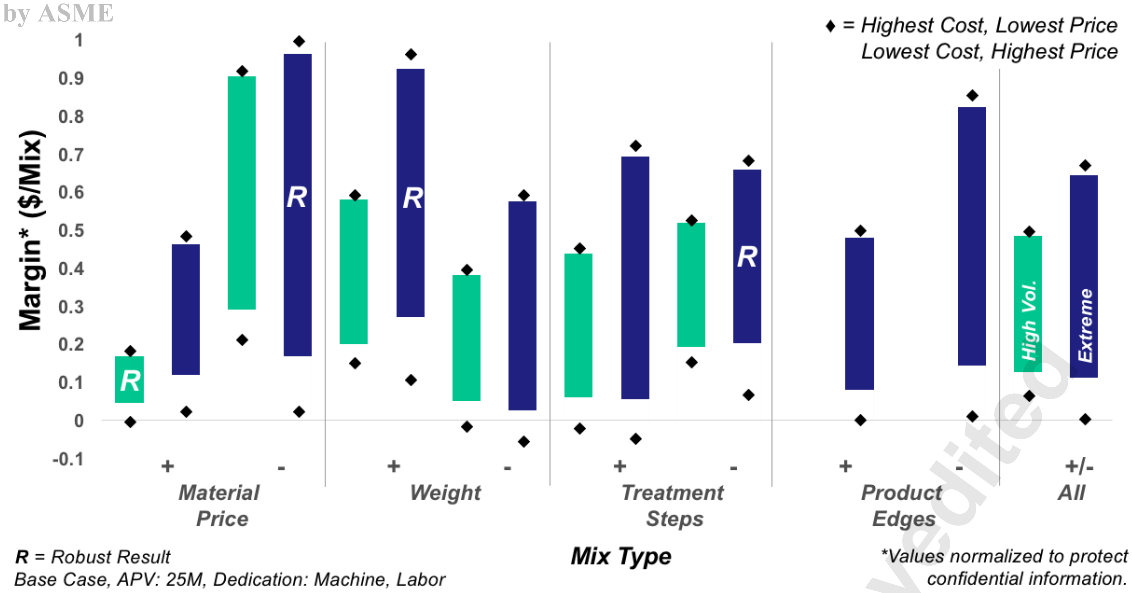

Fig. 3. Using the base case production costs and the high and low extremes of product prices, we find that each mix has a net positive margin. However, once production cost uncertainty is incorporated, several mixes show possible net negative margins, including material(+) in the high-volume DOE and weight(-) and treat(+) in the extreme DOE. The high volume material(+) and extreme material(-), weight(+), and treatment steps(-) results shown are the robust results.

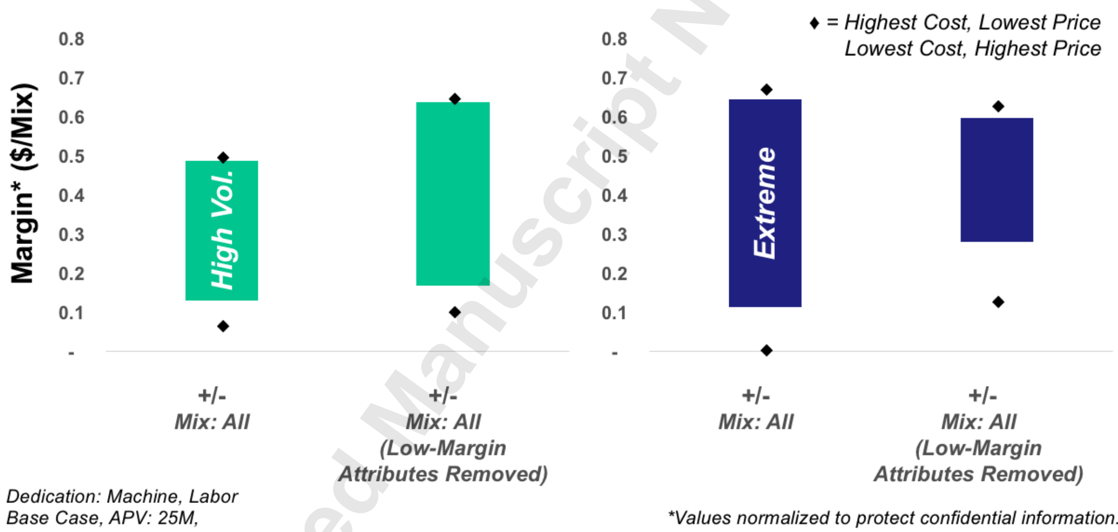

Fig. 4. Using the base case production costs and the high and low extremes of product prices, we find that each mix has a net positive margin. However, once production cost uncertainty is incorporated, several mixes show possible net negative margins, including material(+) in the high-volume DOE and weight(-) and treat(+) in the extreme DOE. The high volume material(+) and extreme material(-), weight(+), and treatment steps(-) results shown are the robust results.

7 Discussion

Our results indicate that for the product mixes considered in the case study, the greatest cost benefits are accrued when producing a high variety of product designs together on a single line. However, to increase their margins, the firm would benefit from removing products with low weight and high treatment steps from the production line with extreme product attributes. If producing only high-volume products, the firm should opt to remove high material price products from the production line. By removing products with these design attributes from the line, the firm improves the lower bound of their

Journal of Mechanical Design. Received April 24, 2018;
Accepted manuscript posted November 09, 2018. doi:10.1115/1.4041943

margins for both sets of products. However, the firm should remove these product designs only if there is enough demand from other products to fully utilize their equipment on the line. Furthermore, the margin analysis includes production cost uncertainty; given that this uncertainty may in part be due to measurement error, the firm should invest in further analysis to confirm cost uncertainties. The study does not account for customers choosing not to purchase one product because another product is cut from the firm′s mix (e.g., as might occur if transaction costs are lower when purchasing multiple products from the same firm). If this loss of demand is significant, it may reduce the firm′s ability to eliminate these products.

If the firm cannot remove these product designs from their portfolio, then they may select products with certain design attributes to produce together on a single line in order to accrue the greatest sharing benefits. In this case, the firm would accrue the greatest sharing benefits from combining products with low weight in the extreme and high-volume DOEs, and high treatment steps (post-consolidation) in the extreme DOE. However, it is worth noting that product mixes with these design attributes may incur net-negative margins, even when combined on a single line, given current sales price ranges and uncertainty in production cost. Parts with high weight and low treatment step (post-consolidation) parts in the extreme DOE may accrue fewer sharing benefits than products with other design attributes. Finally, we find that shared benefits far outweigh changeover costs, particularly if labor and equipment is dedicated to that line.

Our findings also point to the importance of flexible equipment. Flexible equipment may accommodate a wide variety of product designs. The diverse products in our DOEs require a variety of equipment types to accommodate all designs at a single process type. For instance, the extreme DOE all(+/-) mix requires three unique types of forming equipment at the forming step. If one equipment type could accommodate all product designs at a process type, the firm could achieve cost savings of 0.5-5% for each unique process type (SM Section D). With multiple flexible equipment types implemented together across a high-variety mix, the firm could reach cost savings of 4-8%. Because of the large production volumes, this amount of cost reduction is significant in this industry, translating to millions of dollars saved per year. However, this sharing is only possible if the changeover costs between products and lots is not prohibitive. If material contamination concerns, or other time- or yield-prohibitive cleaning or changeover practices increase dramatically when flexible equipment is used, changeover costs may outweigh the benefits derived from sharing flexible equipment across all products in the mix. Changing the lot size may also alter that balance; reducing lot sizes may require additional setup and changeover time and yield loss.

Broadly, our findings point to an important relationship between customized designs and equipment flexibility related to those designs. Equipment and tooling may either be fully dedicated, either to the line or even possibly to a specific product (Fig. 5). When equipment is non-dedicated, it may be perfectly utilized; the production volume may fill all equipment with no additional underutilized time charged to the line. Along that spectrum, fully flexible equipment indicates that while a piece of equipment may be dedicated to a line, it may operate on any product on that line, reducing under-utilization (Fig. 5). In our case, implementing fully flexible equipment can garner a 4% cost reduction in a mix of all extreme products. Alternatively, eliminating labor and machine dedication completely would result in a 5% reduction in cost of the same mix. It is also worth noting that for some non-assembly processes, tooling may be very expensive; in these cases, shared tooling is critical to maintaining cost benefits.

We combine these concepts in Fig. 6. Figure 6 represents four possible regimes along the spectrum of flexibility and lot size, and includes example processes in each quadrant. When lot sizes are large and equipment is dedicated, as in our case study, shared benefits dominate shared costs (Fig. 6). However, if lot sizes are small and equipment may be perfectly utilized, changeover costs dominate (Fig. 6). In cases with small lot sizes and dedicated equipment or large lot sizes and perfect utilization, either shared benefits or changeover costs may dominate, depending on the relative lot sizes and utilization of equipment. A third dimension (not captured above) represents the degree of product variety, as represented in our Design of Experiments axes and space dimensions. For example, in our case study firm, the extreme products represent a higher degree of design differentiation along each axis. As the degree of product variety increases along one or more dimensions,

Journal of Mechanical Design. Received April 24, 2018;
Accepted manuscript posted November 09, 2018. doi:10.1115/1.4041943

Fig. 5. This chart illustrates the spectrum of dedication on the line. Equipment dedication to the line, including specialized designs requiring unique equipment dedication, fall on the left; non-dedication (indicating perfect utilization of the equipment) on the right. Fully flexible equipment would allow products to share equipment, reducing the utilization impacts of dedication. In our case, flexible equipment leads to an approximately 4% reduction in cost for a mix of all products in the extreme case, and full non-dedication amounts to an approximately 5% cost reduction for the same mix.

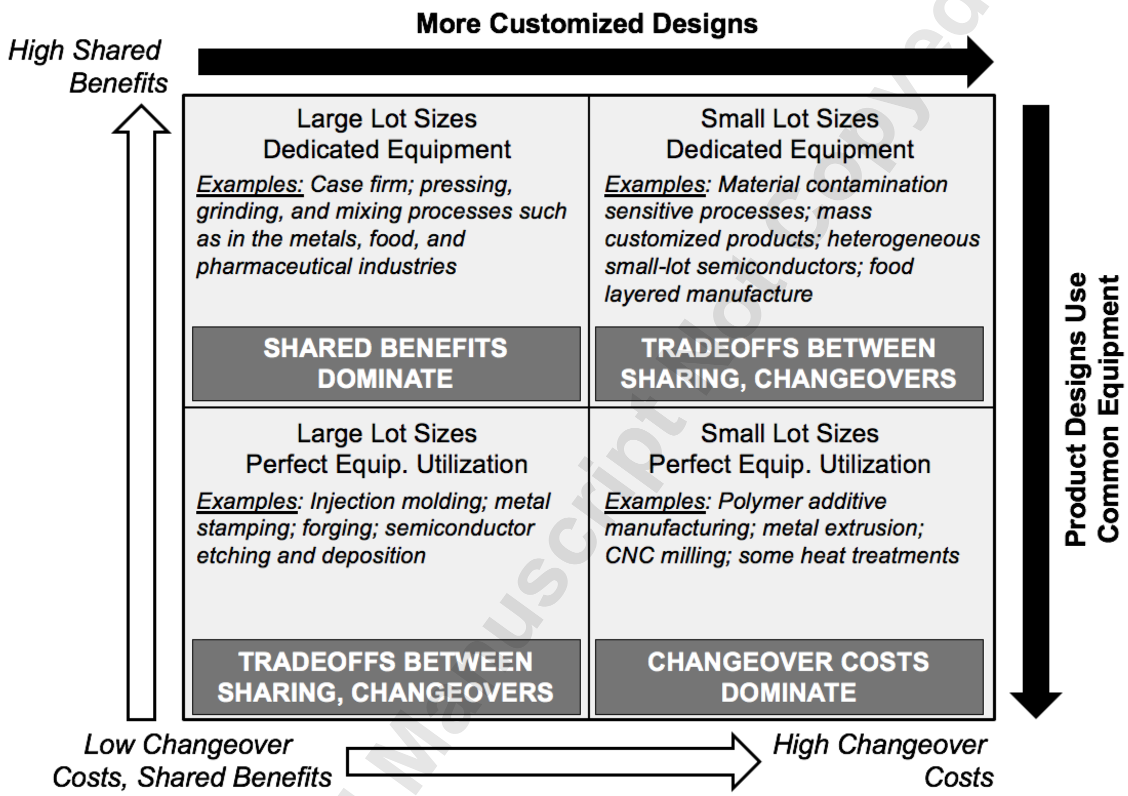

Fig. 6. This chart illustrates the relationship between lot size, utilization, and variety-related costs and benefits. In our case, the large lot sizes and equipment dedication leads to shared costs dominating changeover costs; production falling in the opposite quadrant (small lot size, perfect utilization) would lead to changeover costs dominating shared benefits.

we would expect the magnitude of both shared benefits and changeover costs to also increase.

Given Fig. 6, designers may pursue several strategies to affect production costs. As designs become more customized to the market, they may require more design-specific equipment and lot sizes may be reduced (Fig. 6). However, if designers design products to use common equipment, they may facilitate perfect equipment utilization.

In addition to the generalizability of the frameworks we provide in Figs. 5 and 6, we expect multiple of our specific findings to apply to other types of non-assembled products. First, we believe that treatment and size are the attributes that are also likely to impact other non-assembled production. Many non-assembled products are likely to have multiple treatment processes. If products share processes and have volumes below minimum efficient plant size, mixing products on the line is likely to accrue shared benefits that outweigh shared costs so long as changeover costs remain low (i.e., material contamination or other prohibitive reduction in yields is not a concern). Additionally, in cases where non-assembly products serve as inputs or components to a wide array of end-use products, firms may produce a wide variety of sizes. Given that most types of processing equipment have an upper bound on size capacity, new equipment may be required as sizes extend past a specific range. When designing products, engineers should consider whether a product's size may be accommodated by existing equipment, or whether the design requires new equipment that may not be used by any existing products, limiting the flexibility of the production line.

8 Conclusion

We propose a framework of non-assembled product variety, identifying particular design attributes that drive product variety costs and benefits. Using two sample sets of products, one in the case study firm's high-volume design space and one in the extreme design space, we model costs and benefits related to producing a variety of products on the line. We find that changeover costs associated with product variety are outweighed by the benefits derived from sharing resources among diverse products on a single line. While the specific costs of the case study are particular to this industry and plant, the analysis indicates that shared benefits are likely to dominate in many other production environments which have large lot sizes, dedicated equipment, and low material contamination. We find that producing a variety of products with different sizes, geometries, treatments, and materials on the same line leads to the greatest cost benefits, but small-size and high-treatment products have the lowest margins and could be cut from the mix to increase overall margins. The theoretical framework we develop in this paper is general to most non-assembled products, and could be used in future work to expand understanding of variety and costs in other non-assembled product design.

Acknowledgements

We thank our focus firm for their assiduous help providing data and access to their facility and their financial support of this project. We also thank Pennsylvania Infrastructure Technology Alliance (PITA) and Dave Barakat and LaVerne Owen-Barakat for their financial support of the project. We thank Jeremy Michalek for his advice and guidance on expanding our analysis, as well as Daniel Armanios, Alex Davis, Parth Vaishnav, and the Fuchs and Whitefoot research groups for their feedback. We would also like to thank Frank Field and Michael Johnson for their feedback on our work. Finally, we would also like to thank participants in the Industry Studies Conference and the Technology, Management, and Policy Graduate Consortium, where earlier versions of this work was presented.

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Journal of Mechanical Design. Received April 24, 2018;
Accepted manuscript posted November 09, 2018. doi:10.1115/1.4041943

Supplemental Material for ”Is More Less? Benefits and Costs of High-Variety Production in Non-Assembled Manufacturing”

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Supplemental Material Section A: Process Steps, Inputs, and Data Sources

The PBCM model input types and input sources are listed in this section. Table 1 shows the input types gathered. Some inputs have a range of best/base/worst case values, where they were available or able to be estimated; where there were no best/worst case values available and estimations did not seem prudent, we use the base case value only (in these cases, best and worst sources are not listed). The bulk of the inputs are sourced from the firm, while publicly available data provided energy requirements for equipment use. Where no data were available, we assumed values according to our observations and interviews; these assumptions are noted in Figures 1, 2, 3, 4, 5, 6, 7, 8, and 9. Publicly available data inputs are not explicitly listed here to protect confidentiality, as they refer to specific equipment types and models used by the firm. Finally, this supplemental includes all data used in the model; however, it does not capture the entirety of data collected.

Supplemental Material Section B: DOE and Robustness Checks

DOE:

The selected DOEs (with high and low attribute levels labeled + and -, respectively) may be found in Tables 2 and 3.

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Journal of Mechanical Design. Received April 24, 2018;
Accepted manuscript posted November 09, 2018. doi:10.1115/1.4041943

Table 1. PBCM inputs collected are listed below with their respective units. The sources of these inputs, as well as the processes they were collected for, are contained in Supplemental A.

Input	Units	Input	Units
Load/Unload Time	hr/cycle, lot	Tooling Price	$
Cycle Time	hr/batch	Tooling Replacement Rate	tools/year
Main Equipment Price	$	Auxiliary Equipment Price	$
Equipment Floorspace	square feet	Unplanned Downtime	days/year
Batch Size	parts/batch	Planned Maintenance Downtime	days/year
Labor Dedicated to Process Step	Yes/No	Energy Usage: Up	kW
Labor Required/Cycle	%	Energy Usage: Down	kW
Burdened Wage	$	Fixed Overhead	$
Material Price	$	Maintenance	$
Material Scrap Rate	%	Part Reject Rate	%
Changeover Time Loss	hr/change	Changeover Yield loss	parts/change

Table 2. Three-factor resolution III high-volume DOE design for high-volume design space.

	Attribute:	Material		Size		Treatment	
	Case Measure:	Material Price		Weight		Treatment Steps (Post-Consol.)	
	Units:	($/kg)	Level	Normalized	Level	Quantity	Level
Products	1	37.9	(-)	.05	(-)	8	(+)
	2	37.9	(-)	.13	(+)	5	(-)
	3	44.15	(+)	.02	(-)	4	(-)
	4	44.15	(+)	.12	(+)	10	(+)
	5	44.18	(+)	.05	(-)	8	(+)
	6	44.15	(+)	.11	(+)	4	(-)

Shared Benefits:

We examine robustness checks for three attributes in both DOEs: material price(+) for the high volume DOE, and material price(-), weight(+), and treat (post-consolidation)(-) in the extreme DOE. We find that the results of all substantively change our results, and so include them in the main analysis. We explain these robustness checks and compare them to their non-robust outcomes in the paragraphs below.

Material Price(+), High Volume DOE:

For the material price(+) attribute in the high volume DOE, we eliminate two of the material price(+) products to balance the DOE on the material price attribute. Due to the foldover design, the original analysis contains four material price(+) products. We remove the two foldover products, obtaining a robustness check which has two products in the material

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Table 3. Four-factor Resolution IV DOE for "extreme" products representing the full design space

	Attribute:	Material		Size		Treatment		Geometry	
	Case Measure:	Material Price		Weight		Treatment Steps (Post-Consol.)		Edges	
	Units:	($/kg)	Level	Normalized	Level	Quantity	Level	Number Of	Level
Products	1	37.9	(-)	.04	(-)	5	(-)	8	(-)
	2	78.9	(+)	.03	(-)	7	(-)	12	(+)
	3	44.15	(+)	1.0	(+)	4	(-)	8	(-)
	4	39.9	(-)	.11	(+)	10	(+)	12	(+)
	5	43.26	(-)	.93	(+)	10	(+)	8	(-)
	6	37.9	(-)	.02	(-)	10	(+)	12	(+)
	7	71.8	(+)	.03	(-)	8	(+)	8	(-)
	8	37.9	(-)	.86	(+)	3	(-)	12	(+)

price(+) attribute level. We compare the results of this robustness check to the original material price(+) result, and find that the robustness check indicates there is not a substantial difference in shared benefits when additional material price(+) products are removed (Fig. 10). As such, we elect to use the robustness check results.

Material Price(-), Extreme DOE:

In the extreme DOE, the DOE contains a non-adherent material price(-) corner, which should be material price(+). This non-adherent corner creates two problems. First, the non-adherent corner (product E4) leads to an non-adherent DOE. Second, it creates an imbalanced DOE, with three material price(+) products and five material price(-) products. We test both of these issues in our robustness checks, first eliminating the non-adherent corner, and then eliminating both the non-adherent corner and an additional material price(-) product, creating a balanced DOE with three products in the (+) and three products in the (-) levels of the material price attribute. The results indicate that removing both the non-adherent corner in addition to another product to balance the DOE eliminates the large difference between material price(+) and material price(-) (Fig. 11). As such, we use the robustness check results with the balanced DOE in our results.

Weight (+), Extreme DOE:

The DOE selected includes four weight (+) products, one of which is substantially lower in weight than the others. We test the effect of removing this product, re-running the benefits analysis for weight while removing the weak weight (+) product (E4). In doing so, we find the robust weight (+) result to be substantially lower in shared benefits than weight (-) (Fig. 12). As such, we elect to use the robust result in our main analysis.

Treatment Steps (Post-Consolidation): (-), Extreme DOE:

Our DOE contains a weak treatment steps (-) level in product E2. To test the effect of removing this weak corner, we run a robustness check on treatment steps (-) with the weak corner removed. After comparing the robust and non-robust results, we find that removing the weak corner results in a large difference between treatment steps (-) and treatment steps (+) shared benefits (Fig. 13). As such, we show the robust results in our main analysis.

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Changeover, Total Costs (Edges (+) and Edges (-), Extreme DOE):

Because number of edges exhibit a large difference in changeover costs between their levels, we ran an additional robustness check to determine whether the difference was an artifact of a disproportionately high-weight mix (likely made more disproportionate by the weak weight (+) product contained in the edges (+) mix). To test this effect, we removed a part from each mix, including one high-weight product from the treat (-) mix and its orthogonal product in the treat (+) mix. We examine the resulting change in changeover costs, and find that the changeover costs are now balanced (Fig. 14). This indicates that the disproportionately high edges (-) changeover cost is impacted by the imbalanced weights discussed previously.

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Accepted manuscript posted November 09, 2018. doi:10.1115/1.4041943

Supplemental Material Section C: Process Based Cost Model

PBCM examines costs as a function of material, design, and process decisions, and has been used in various industries, from photonic and electronic semiconductor chip design [?, ?, ?] to composite auto body production and assembly [?, ?], to printed circuit board and optoelectronic transceiver fabrication and assembly [?, ?, ?] to Li-ion batteries [?] to metal additive manufacturing [?]. PBCM has also quantified impacts of parts consolidation and material choices, as well as shared costs and commonality metrics within product families [?, ?, ?].

The PBCM is made up of decision rules, inputs, and the model architecture. As noted in [?], the model architecture is the organization of the inputs and decision rules; the architecture itself has no impact on cost [?]. The model decision rules are the mathematical equations which form the relationships between the inputs and outputs. This supplemental elaborates on the decision rules unique to this model; these rules build on the rules found in [?]. The decision rules capture the data inputs, simulating each process step, and the interactions between each step, for a given product. For a specified APV of good parts of a specific product, the model captures the production inputs required, given the manufacturer′s capabilities, to achieve a target number of good units per year, including capital, building, labor, material, energy, and maintenance. We then multiply these factor input requirements by their prices (e.g. machine prices, wages, energy prices, material prices, building prices, etc.) to find a total annual cost.

The following section relates engineering design decision rules to their related processes, operations, and thus costs. Combined with the input data collected at the firm, these decision rules determine the cost of producing ”good” (e.g., salable) outputs. This section builds on the definitions and equations provided in [?], which ultimately calculate cost for a specified volume of outputs given inputs gathered from the firm.

The following table summarizes the major variable names to guide readers as they continue to read through the supplemental. Terms are also reviewed as they are listed in the equations.

Summary Table: Major Variable Names

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Major Variables	Definition
i	Indicates the count of the process step in a process flow for lot j
n	Indicates the total number of process steps in lot j
j	Indicates the count of the lot number in the plant annual schedule
k	Indicates the set of products being modeled
p	Indicates the type of specific processes being modeled
m	Indicates the type of specific substrate materials used
APV	Indicates the annual production volume of good parts desired
LPV	The total desired production volume of good parts in a lot (not annual)
LTA	The line time available given plant and labor downtimes
NS	Hours with no shifts (could be plant or process-specific)
UB	Hours with unpaid breaks at the plant
PB	Hours with paid breaks at the plant
MT	Days of planned maintenance time (could be plant or process specific)
UD	Unplanned downtime in days per year (could be plant or process specific)
DPY	Working days per year at the plant
effPV	The total volume of ”good” parts at a process
T^{ch}	Additional time required due to the changeover between products at a process
T^{y}	Cycle time at a process
T^{u}	Setup time, load, and unload time at between runs at a process step
r	Rate of rejected pieces (in percent) at a process step
L^{ch}	Number of rejected (lost) pieces due to changeovers between products at a process step
batch	The batch size (in number of parts) at a process step; may be product specific
reqLT	The required line time (in hours) at a process step
LR_p	The lines required of a process type
U	Generally denotes usage; usage could refer to processes, energy, labor, or material
x	the amount of material required at a given step that winds up on the final product k
s	the scrap rate of an introduced material (in %) at a given process step
P	The price per unit of respective investments, including labor, material (in $/kg), energy (in kW), capital, and buliding costs

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Major Variables	Definition
crf	Capital recovery factor to calculate stream of payments
r	selected discount rate
N	Number of years over which to amortize the purchase
R	Value of the constant payment
M	Machine type
A	Auxiliary equipment
B	Building
F	Fixtures and tooling
maint	Maintenance
OH	Overhead
El	The elements of the total cost, including: Material, labor, machine, auxiliary equipment, tooling, building, maintenance, and overhead.
AC	Annual Cost
C	Unit cost; only used for single-product-type calculations

Time Equations

We begin by defining several key time-related variables, which, combined with the two key material variables, will be the foundation of our set of decision rules. First, the plant-wide available line time (LTA) is the time available in one year for producing parts, whether those parts are good or bad. This time accounts for other plant downtimes, operator break times, and maintenance requirements facility-wide. We calculate available line time as:

Line Time Available at step p:

$$LTA_p = (DPY - UD - UD_p - MT_p) * (24 - NS_p - UB_p - PB_p) \tag{1}$$

Where:

$$DPY = Working\, days\, per\, year\, at\, the\, plant$$
$$UD = Unplanned\, down\, time\, in\, days\, per\, year\, at\, the\, plant$$
$$UD_p = Unplanned\, down\, time\, in\, days\, per\, year\, at\, the\, process\, step$$
$$MT_p = Planned\, down\, time\, for\, maintenance\, in\, days\, per\, year\, at\, the\, process\, step$$
$$NS_p = Hours\, per\, day\, without\, shifts\, at\, the\, process\, step$$
$$UB_p = Unpaid\, break\, hours\, per\, day\, at\, the\, process\, step$$
$$PB_p = Paid\, break\, hours\, per\, day\, at\, the\, process\, step$$

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The effective production volume (effPV) is the number of total parts that need to be initiated to produce the total Annual Production Volume (APV), the specified number of "good" parts per year. Effective production volume takes into account reject rates over the entire process. In our particular case, the effPV is calculated at the lot level (j), and also accounts for parts lost after transitioning from one product to the next at a specific process step (called the changeover part loss, $L^{ch}{}_{p,k,k_{j^p-1}}$). This yield loss is specific to the process type p, and the product k of the lot being calculated, as well as the previous product k at process p. The calculation of effective production volume at the lot level (j) is representative of the firm′s production process: unique products are produced in groups of several dozen to several thousand pieces at a time. Each group is labeled a lot, and the lot travels through the full production process together. All lots are limited to one product only.

The full equation for effective production volume at step i of lot j of a specific product k is shown below; the effective production volume for the penultimate step is the total lot production volume for lot j (LPV_j) divided by the yield rate of the penultimate step.

Key Variables: Production

Several key variables have already been defined by [?]; we build on these definitions in the following equations.

We define several primary variables related to material upon which we build our equations. To understand material losses, we define reject rate at a particular step i ($r_{p,k}$) as the fraction of "bad" parts of unacceptable quality which will not proceed to future steps. We define the yield at a particular process type p for product k ($Y_{p,k}$) to be the percentage of "good" parts which proceed to successive steps in the process. Given these definitions, the following equation denotes yield:

$$Y_{p,k} = 1 - r_{p,k} \tag{2}$$

The loss of parts at a specific process type p results in the loss of equipment and labor time, not only for that particular process type p, but also the loss of all time and resources invested in the part prior to the step at which it is rejected. While a problem may occur in a part at a step prior to the step at which a part is rejected, it is accounted for at the step it is rejected, thus incurring cost until the part′s flaws are identified.

In addition to, but critically different from, reject rates, we define scrap rate of a given material m at a specific step i ($s_i{}^m$) to be the percentage of a specific material lost at a process type p (e.g., material that is not included in the final product). Scrap rates represent only material lost or removed in process (e.g., powder that falls on the floor in addition to material ground off for shaping), and not any additional resources required to produce the part up to step i. The cumulative scrap rate is calculated and accounted for at the step at which the material enters the process, incorporating future steps′ material loss to properly account for the full amount of material required to produce the final good part (less any lost material).

Effective Production Volume

Effective Production Volume (effPV) at step i of product k′s process flow at lot j:

$$effPV_{i,j,k} = \left\lceil \frac{effPV_{i+1,j,k}}{1 - r_{p,k}} \right\rceil + L^{ch}{}_{p,k,k_{j^p-1}} \tag{3}$$

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Where:

$$effPV_{i+1,j,k} = The\,effective\,production\,volume\,for\,lot\,j\,at\,the\,process\,step\,previous\,to\,i\,for\,product\,k$$
$$r_{p,k} = The\,reject\,rate\,for\,product\,k\,at\,process\,p$$
$$L^{\mathrm{ch}}{}_{\mathrm{p,k,k_{j^p-1}}} = The\,yield\,loss\,(a\,whole\,number)\,due\,to\,changing\,products\,at\,step\,i\,to\,product\,k\,from\,the\,previous\,product\,on\,the\,equipment$$

Given the value above, the plant-wide or product-specific total effective production volume can be found by summing the effective production volume across all lots or all product-specific lots, respectively.

With the total available line time and effective production volumes calculated, we must then find the line time required at step i over the course of a year to produce the required effective production volume of product k. This is the amount of time required to produce the desired final number of annual "good" parts, or APV. There are two primary equations, on representing the required line time for batched production steps (such as coating and consolidation) and one representing continual throughput production steps (such as shaping or surface treatment), which continually push through small flows (either one or very few pieces), but which may require a tooling or fixture change between lots. These two types of production steps are captured in the equations below:

Required Line Time

Required Line Time (reqLT) for batched product k at step i of lot j:

$$reqLT_{p,j,k} = \frac{effPV_{i,j,k}}{batch_{i,k}} * (T_{p,k}^{y} + T_{p}^{u}) + T_{p}^{o} + T^{\mathrm{ch}}{}_{\mathrm{p,k,k_{j^p-1}}} \tag{4}$$

Where, given facility observations, if:

$$batch > 1, T_p^o = 0 \tag{5}$$

$$batch = 1, T_p^u = 0 \tag{6}$$

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Where:

$$effPV_{i,j,k} = The\,effective\,production\,volume\,at\,step\,i\,specific\,to\,the\,production\,lot\,j$$
$$batch_{i,k} = The\,batch\,size\,at\,step\,i\,specific\,to\,product\,k$$
$$T_{p,k}^{y} = Cycle\,time\,at\,step\,i$$
$$T_{p}^{u} = Setup\,time\,at\,step\,i\,for\,batches\,greater\,than\,1$$
$$T_{p}^{o} = Time\,required\,to\,change\,between\,different\,lots\,o\,at\,step\,i\,for\,batches\,equal\,to\,1$$
$$T^{ch}{}_{p,k,k_{j^{p}-1}} = The\,time\,spent\,to\,change\,products\,at\,step\,i\,to\,product\,k\,from\,the\,previous\,product\,on\,the\,equipment$$

This equation incorporates the effective production volume of step i, the batch size for process p, the cycle time and setup time required for the batch, as well as any additional time required to setup the machine at i for product k from product k-1. Given that $T^{ch}{}_{p,k,k_{j^{p}-1}}$ will change based on which product preceded k at process p, required line time at process p for any given lot j will vary.

From here, we are able to calculate the lines required (LR) at any given step i to produce the desired number of good parts (APV) per year for a product k (APV_k). In this case, we calculate the lines required through parallel production, where multiple machines may be performing the same task at once. Alternatively, additional production volume may be produced by breaking tasks down into smaller increments of machine/labor combinations. Our case study will utilize parallel production, as seen in the following equation:

Lines Required

Lines required (LR):

$$LR_p = \frac{\Sigma_{jk} reqLT_{p,j,k}}{LTA} \tag{7}$$

Where:

$$LTA = The\,plant\,wide\,line\,time\,available$$

Variable Cost Equations

Material

The per product usage ($U_{i,k}{}^{m}$) for material type m at step i (the step at which the material is introduced into the process) is calculated in the following equations. In our particular case, m is the substrate metal powder that comprises the piece.

Material Usage at step i (where material m is introduced):

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$$U_{i,k}^{\ m} = \frac{x_{i,k}^{\ m}}{\Pi_i^n (1 - s_{i,k}^{\ m})} \tag{8}$$

Where:

$$x_{i,k}^{\ m} = The\, amount\, of\, material\, m\, required\, on\, the\, final\, product\, k\, introduced\ : at\, step\, i$$
$$s_{i,k}^{\ m} = The\, scrap\, rate\, (in\, percent)\, of\, total\, material\, m\, used\, on\, product\, i\, that\, does\, not\, end\, up\, in\, the\, final\, product$$

As noted previously, individual scrap rates for material m for each process step i are multiplied and accounted for at step i, thus accounting for all subsequent material loss at the time the material is introduced.

Annual Material Usage (AU_p^m) sums the usage per piece of product k across all production volume at process p that is comprised of material m:

$$AU_{p,k}^{\ m} = \Sigma_j effPV_{i,j,k}^{\ m} * U_{p,k}^{\ m} \tag{9}$$

Annual Material Cost (AC_p^m) then multiplies the usage of material m by the price of material m to get the total annual cost of material m at process p:

$$AC_p^m = P^m * AU_p^m \tag{10}$$

Consumables - materials which are introduced and completely consumed in the course of production at the same step - were accounted for in fixed costs as a part of fixtures and tooling.

Labor

To understand the calculations for labor usage, we must first define a key term: L_p indicates the fractional use of labor, or the fraction of time an operator must be at the machine at process p to set up, load, unload, and oversee production. In some cases, L_p is less than 100%, which means the operator is not attending the machine at all times (and may thus be shared across other equipment, depending on dedication). If L_p is greater than 100%, more than one operator may be required to oversee the station or machine. In this particular case, ”dedicated” labor indicates that the operator may be shared among identical process steps (e.g., across machines of process p), but may not be shared among other process steps. Non-dedicated labor indicates that the operator may be shared among various different process steps on the line.

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Total annual labor usage at process p for labor type l:

$$AU_p^l = \left\lceil L_{p,dedicated}^l * LR_p \right\rceil^{L_p^l} + L_{p,non-dedicated}^l * LR_p \tag{11}$$

Where:

$$l = Indicates\, the\, labor\, type,\, l$$
$$L_p = The\, fraction\, of\, labor\, required\, on\, the\, line\, to\, adequately\, operate\, process\, p$$
$$LR_p = The\, lines\, required\, at\, process\, p$$

From here, the annual paid time at process p may be calculated for all labor type l:

$$APT_p^l = DPY * (24 - NS - UB) * AU_p^l \tag{12}$$

Where:

DPY = Days per year of operation

NS = Hours of no shifts in a day

UB = Hours of unpaid breaks in a day

And labor cost at process p:

$$AC_p^l = APT_p^l * P_p^l \tag{13}$$

Where:

$$P^l = Indicates\, the\, price\, of\, labor\, type\, l$$

The energy usage at process p (U_p^e) can be separated into two categories: energy usage in kW while the equipment p on and running ($U_p^{e,on}$), and energy usage in kW while the equipment is idle ($U_p^{e,idle}$). For all process steps, we assume that idle energy usage is 0. Given this, we define the annual energy usage as follows:

Annual energy usage at process p for product k ($AU_{p,k}^e$):

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$$AU_p^e = [(\Sigma_{jk} reqLT_{p,j,k} * U_p^{e,on}) + (DPY * U_p^{e,idle})] \tag{14}$$

Where:

$$e = Indicates\,usage\,is\,specific\,to\,energy$$
$$on = Indicates\,the\,equipment\,is\,in\,use$$
$$idle = Indicates\,the\,equipment\,is\,not\,in\,use$$

From here, we can calculate the annual energy cost (AC_p^e) by multiplying the annual energy usage (AU_p^e) by the price of energy:

$$AC_p^e = P^e * AU_p^e \tag{15}$$

Where:

$$P^e = The\,price\,of\,energy\,in\,\$/kWh$$

Fixed Cost Equations

To calculate fixed costs, such as capital investments, we must take into account the time value of money. We find the value of constant payments (R) required over a specified number of payments (N, typically the lifetime of the capital) by using the discount rate (r) and the price (P) of the equipment. Using these elements, we calculate the capital recovery factor (crf), from which we calculate R:

Capital

Capital Recovery and Stream of Payments:

$$crf = \frac{r * (1+r)^N}{(1+r)^N - 1} \tag{16}$$

$$R = P(crf) \tag{17}$$

Where:

$$R = Value\,of\,each\,constant\,payment$$
$$r = Selected\,discount\,rate$$
$$N = Number\,of\,years\,over\,which\,to\,amortize\,the\,purchase$$
$$P = The\,price\,of\,the\,capital\,investment\,in\,question$$

We assume a discount rate of 7%, a capital lifetime of 15 years, and a building lifetime of 50 years. Using these equations, we can proceed calculating our fixed costs, which include main machine, auxiliary equipment, and building costs (the prices of which are unique to each capital expenditure, noted as $P^M{}_p$, $P^A{}_p$, and $P^B{}_p$ for process p). These costs are primarily affected by the time required at each step i and the yield lost at each step i. When additional time, whether for product processing or downtime, is required at the process step, more machines are required to cover the total line time required at step i. Similarly, additional yield loss requires more product to be initiated in order to produce the desired number of "good" parts. Thus, additional machines will be required to cover that loss. In our particular case, we have factored in additional time and yield losses due to changeovers between different products. This has been noted in the line time required, and also affects capital costs.

To calculate annual main machine (capital) costs at process p, we sum the dedicated and non-dedicated annual costs for the main machine and auxiliary equipment at process p:

$$AC_p^M = AC_{p,dedicated}{}_d^M + AC_{p,non-dedicated}{}_d^M \tag{18}$$

$$AC_p^A = AC_{p,dedicated}{}_d^A + AC_{p,non-dedicated}{}_d^A \tag{19}$$

Where:

$$AC_p^M = Indicates\,the\,annual\,cost\,for\,the\,main\,machine\,at\,process\,p\,for\,product\,k$$
$$AC_p^A = Indicates\,the\,annual\,cost\,for\,the\,auxiliary\,equipment\,at\,process\,p\,for\,product\,k$$

As in the labor equations, we see that equipment may be dedicated and non-dedicated. Dedicated equipment indicates that the machine is only used for the products in question on the line; e.g., the cost is fully absorbed by the products we are analyzing. Non-dedicated capital indicates that the machine may produce other products on the line when not producing the parts being analyzed. As such, the costs may be spread across multiple products (and thus are not fully allocated to the products being analyzed), as we see below:

Annual Dedicated, Non-Dedicated Main Machine Cost and Auxiliary Equipment Cost:

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$$AC_{p,dedicated_d}^{M} = R_p^M * U_{p,dedicated_d}^{M} = R_p^M * \lceil LR_p \rceil \tag{20}$$

$$AC_{p,non-dedicated_d}^{M} = R_p^M * U_{p,non-dedicated_d}^{M} = R_p^M * LR_p \tag{21}$$

Auxiliary Equipment

Annual Auxiliary Equipment Costs:

$$AC_{p,dedicated_d}^{A} = R_p^A * U_{p,dedicated_d}^{A} = R_p^A * \lceil LR_p \rceil \tag{22}$$

$$AC_{p,non-dedicated_d}^{A} = R_p^A * U_{p,non-dedicated_d}^{A} = R_p^A * LR_p \tag{23}$$

Where:

$$M = MainMachine$$
$$A = AuxiliaryEquipment$$
$$R_p = Represents\,the\,stream\,of\,annual\,payments\,required\,for\,equipment\,p$$
$$U_p = Represents\,the\,usage\,required\,at\,equipment\,p$$
$$LR_p = Represents\,the\,lines\,required\,of\,equipment\,p$$

Building

Building costs are calculated similarly. Annual building costs:

$$AC_p^B = R_p^B * (AU_{p,dedicated_d}^{B} + AU_{p,non-dedicated_d}^{B}) \tag{24}$$

$$AU_{p,dedicated_d}^{B} = \lceil LR_p \rceil * DimensionsPerLine_p \tag{25}$$

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$$AU_{p,non-dedicated}{}^{B} = LR_p * DimensionsPerLine_p \tag{26}$$

Where:

$$\begin{aligned}
B &= Building \\
R_p^B &= Represents\,the\,stream\,of\,annual\,payments\,required\,for\,building\,space \\
AC_p &= Represents\,the\,annual\,cost\,of\,building\,space\,required\,of\,equipment\,p \\
AU_p &= Represents\,the\,annual\,usage\,of\,building\,space\,required\,of\,equipment\,p \\
&for\,product\,k \\
LR_p &= Represents\,the\,lines\,required\,of\,equipment\,p \\
DimensionsPerLine_i &= Equals\,the\,floorspace\,needed\,(in\,square\,feet)\,for\,equipment\,p
\end{aligned}$$

Fixtures and Tooling

We can find the costs of fixtures and tooling via similar equations. Tooling, in our case, is always dedicated. Tooling usage is equivalent to the tools per line times the lines required. The usage is then multiplied by the price per fixture or tool.

Annual Fixtures and Tooling Costs (all assumed to be dedicated, given the way the data were collected):

$$AC_p^F = P_p^F * AU_p^F \tag{27}$$

$$AU_p^F = ToolsPerLine_p^F * \lceil LR_p \rceil \tag{28}$$

Where:

$$\begin{aligned}
F &= Fixturesandtooling \\
P_p^F &= Represents\,the\,stream\,of\,annual\,payments\,required\,for\,fixtures\,and\,tooling \\
AC_p^F &= Represents\,the\,annual\,cost\,of\,fixtures\,and\,tooling\,required\,of\,equipment\,p \\
AU_p^F &= Represents\,the\,annual\,usage\,of\,tooling\,and\,fixtures\,required\,of\,equipment\,p \\
&for\,product\,k \\
LR_p &= Represents\,the\,lines\,required\,of\,equipment\,p \\
ToolsPerLine_p &= Equals\,the\,tools\,needed\,annually\,for\,equipment\,p
\end{aligned}$$

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Maintenance

Annual maintenance costs are assumed to be a percentage of the annual costs of the main machine, auxiliary equipment, fixtures/tooling, and building costs for process p. In this case, we assume the percentage to be approximately 10% of the sum of those values:

Annual maintenance costs:

$$AC_{p,k}^{maint} = 10\%(AC_p^M + AC_p^A + AC_p^F + AC_p^B) \tag{29}$$

As with maintenance, annual overhead costs are assumed to be a percentage of the annual costs of the main machine, auxiliary equipment, fixtures/tooling, and building costs for process p. In this case, we assume the percentage to be approximately 30% of the sum of those values:

Overhead Costs

Annual overhead cost:

$$AC_{p,k}^{OH} = 30\% * (AC_p^M + AC_p^A + AC_p^F + AC_p^B) \tag{30}$$

Each of the equations above are combined to represent the value of the annual cost elements (El) for each product, k, at each lot, j. The unique cost elements are: Material, labor, energy, machine, auxiliary equipment, tooling, building, maintenance, and overhead.

From these elements, we can calculate a total cost for an annual mix by summing all cost elements over all processes:

Where:

$$AC_{Total}^{El} = \Sigma_p AC_p^{El} \tag{31}$$

And:

$$El = [Material, labor, energy, machine, auxiliary\,equipment, tooling, \\ building, maintenance, and\,overhead$$

Finally, the cost per part (the average cost of all unique parts k in the mix) can be found via the following equation:

And:

$$C_{Unit}^{El} = \frac{AC_{Total}^{El}}{APV} \tag{32}$$

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Supplemental Material Section D: Equipment Flexibility

Within the firms broad processes (grinding, surface treatment, etc.), the firm uses many unique equipment types to process unique products. We use the firms specified equipment type for each product in our base case. However, equipment may be underutilized on the line if it may not be used for all products. In this case, the firm would require greater investment and possibly additional labor specialization, leading to increased production costs. To understand the impact of equipment variation within process steps, we unify equipment type across each individual process step for all products in the All mix of the extreme DOE. For this mix, we ensure only one equipment type at each process step is required on the line. We perform this analysis individually across five steps: forming, part consolidation, shaping, and two types of grinding (A and B). Finally, we perform this analysis on all steps together. As we are maintaining the products produced on the line but hypothesizing that equipment may be used across all products, we identify this as ”equipment flexibility”.

To understand the effects of flexible equipment on these product sets, we find the percent total annual cost reduction using flexible equipment for each DOE′s high-variety mix, the all(+/-) mix. We examine cost reductions associated with enabling flexibility in six high-price and high-labor pieces of equipment, and then calculate the cost reduction from implementing all six flexible equipment types at once (Fig. 15). We find that both mixes accrue cost savings from implementing individual pieces of flexible equipment, with the greatest cost savings coming from implementing all pieces of flexible equipment on the line at once.

Supplemental Material Section E: APV and Dedication Sensitivity Analyses

To understand the impacts of sharing labor between processes, or letting idle equipment be used by other lines when the product mix′s APV is completed, we ran each mix at different levels of dedication. We find that if labor or equipment are non-dedicated, the benefits accrued from sharing are reduced (Figs. 16, 17). If both are non-dedicated at once, the sharing benefits essentially disappear. This result is expected, as the source of our shared benefits arise from increased equipment utilization when the equipment is dedicated.

Next, we run our model at a range of APVs to examine how benefits change with volume. We find that the trends we observe in the difference between shared benefits across different attribute levels broadly hold (Figs. 18, 19). The diversity in benefits within attributes reflects different levels of utilization at different annual production volumes.

Supplemental Material Section F: Annual Mix Costs, Product Unit Costs, and Mix vs. Standalone Comparison

We include annual mix costs for each mix and unit cost breakdowns of each individual product in this supplemental. All values reflect the base case scenario for each input only; additional visualizations on the unit cost ranges can be found in Supplemental G.

Figure 20 shows the total annual cost of each DOEs annual product mixes. The extreme DOE generally exhibits higher annual costs than the high-volume DOE, likely due to the higher product weights. Among all attributes, several appear to have large discrepancies between their (+) and (-) product mixes. First, in the extreme DOE, weight(+) appears to have a significantly higher cost than weight(-), primarily due to the larger amount of material required to produce the products. The extreme DOE also exhibits a higher cost for edges(-) than edges(+); because the DOE contains weak corners that may exhibit trends in other attributes, we ran a robustness check to confirm that this trend was not changed with the weak corners removed (included in Supplemental B). We found that the trend was weakened, but not reversed, in the robustness check. Additionally, we find material(+) to be less than material(-) both DOEs. Finally, the treatment(+) mix appears to have a larger cost than treatment(-) in the high volume DOE, but the opposite trend is seen in the extreme DOE.

Figure 21 shows the unit cost of each product. Higher weight products incur higher costs (see E3, E5, and E8), with costs primarily driven by material. Low weight products with low material price/kg have a much higher proportion of cost

Journal of Mechanical Design. Received April 24, 2018;
Accepted manuscript posted November 09, 2018. doi:10.1115/1.4041943

driven by labor and machine price. While the extreme DOE products exhibit some higher costs, many fall in similar ranges as the costs found in the high-volume DOE. Overall, our unit cost results indicate weight and and treatment primarily drive unit cost and the unique unit cost breakdowns. Product-level margins are listed in Fig. 22. These margin ranges are calculated as described in the methods section.

Supplemental Material Section G: Product Cost Curves

We include a series of unit cost curves for each of the 14 selected DOE products, below. Each graph contains two lines, the worst-case upper bound and best-case lower bound scenarios for each product. The spikes in the curves show where new equipment is added (since the equipment is dedicated; as the APV increases, the cost of a machine is spread across more parts, lowering the unit cost, until an additional piece of equipment is required to accommodate additional volume). Figures 25 and 26 show the cost curves for the extreme products. Figures 23 and 24 show cost curves for the high volume products. Minimum efficient plant size is reached at between two and five million parts per year.

Supplemental Material Section H: Heat Maps

This supplemental lists the heat maps discussed in the results section. Figures 27, 28, 29, and 30 list the weight, edges, material, and treatment attributes, respectively.

Supplemental Material Section I: Lot Size

This supplemental contains figures that show where changeover costs outweigh shared benefits as lot size changes (Figs. 31 and 32). This occurs between five and ten parts per lot for both the extreme and high-volume DOE "all" mixes.

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		Coat A 1	Coat A 2	Coat A Prep	Coat B 1	Coat B Prep	Consolidation 1	Consolidation 2	Consolidation Prep
Cycle Time	Best	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee
	Base	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee
	Worst	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee
Load/Unload Time	Best	Firm Employee	Firm Employee	-	Firm Employee	-	Firm Employee	Firm Employee	Firm Employee
	Base	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee
	Worst	Firm Employee	Firm Employee	-	Firm Employee	-	Firm Employee	Firm Employee	Firm Employee
Changeover Times, Yields (Product Specific)	Best	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee
	Base	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee
	Worst	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee
Main Machine Floorspace	Best	-	-	Author Estimate	-	Assumption (Base-10%)	Assumption: -10%	Assumption: -10%	Assumption: -10%
	Base	Estimate based on Equipment Specs {A}	Estimate based on other coating equipment	Author Estimate	Estimate based on Equipment Specs [B]	Author Assumption	Estimate based on engineering drawings	Estimate based on engineering drawings	Estimate based on engineering drawings
	Worst	-	-	Author Estimate	-	Assumption (Base+10%)	Assumption: +10%	Assumption: +10%	Assumption: +10%
Batch Size/Shift Throughput	Best	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee
	Base	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee
	Worst	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee
Main Machine Price	Best	Estimate based on Historical Asset Costs	Estimate based on Historical Asset Costs	Assumption (Base-10%)	Estimate based on Historical Asset Costs	-	Estimate based on Historical Asset Costs	Estimate based on Historical Asset Costs	Assumption: -10%
	Base	Estimate based on Historical Asset Costs	Estimate based on Historical Asset Costs	Estimate based on Historical Asset Costs	Estimate based on Historical Asset Costs	Author Assumption	Estimate based on Historical Asset Costs	Estimate based on Historical Asset Costs	Estimate based on Historical Asset Costs
	Worst	Estimate based on Historical Asset Costs	Estimate based on Historical Asset Costs	Assumption (Base+10%)	Estimate based on Historical Asset Costs	-	Estimate based on Historical Asset Costs	Estimate based on Historical Asset Costs	Assumption: +10%
Fraction of Labor	Best	Firm Employee	Firm Employee	-	-	-	-	-	-
	Base	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee
	Worst	Firm Employee	Firm Employee	-	-	-	-	-	-
Labor: Burdened Wage	Best	-	-	-	-	-	-	-	-
	Base	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee
	Worst	-	-	-	-	-	-	-	-
Labor Dedication	Best	-	-	-	-	-	-	-	-
	Base	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee
	Worst	-	-	-	-	-	-	-	-
Material Type	Best	-	-	-	Firm Employee	-	-	-	-
	Base	-	-	-	Firm Employee	-	-	-	-
	Worst	-	-	-	Firm Employee	-	-	-	-

Fig. 1. This table lists the assumptions and sources of inputs in the model.

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		Coat A 1	Coat A 2	Coat A Prep	Coat B 1	Coat B Prep	Consolidation 1	Consolidation 2	Consolidation Prep
Material Use Rate	Best	-	-	-	Firm Employee	-	-	-	-
	Base	-	-	-	Firm Employee	-	-	-	-
	Worst	-	-	-	Firm Employee	-	-	-	-
Tooling Price	Best	Firm Employee	Firm Employee	-	Firm Employee	-	Authore Estimate based on Employee Discussion	Authore Estimate based on Employee Discussion	-
	Base	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Author Estimate	Authore Estimate based on Employee Discussion	Authore Estimate based on Employee Discussion	Firm Employee
	Worst	Firm Employee	Firm Employee	-	Firm Employee	-	Authore Estimate based on Employee Discussion	Authore Estimate based on Employee Discussion	-
Replacement Rate	Best	-	-	-	-	-	Authore Estimate based on Employee Discussion	Authore Estimate based on Employee Discussion	-
	Base	Firm Employee	Firm Employee	Firm Employee	Firm Data	Author Estimate	Authore Estimate based on Employee Discussion	Authore Estimate based on Employee Discussion	Firm Employee
	Worst	-	-	-	-	-	Authore Estimate based on Employee Discussion	Authore Estimate based on Employee Discussion	-
Auxiliary Equipment Price	Best	-	-	-	-	-	Assumption (Base-10%)	Assumption (Base-10%)	-
	Base	Firm Data	Firm Data	Firm Data	Firm Data	Firm Data	Firm Data	Firm Data	Assumption
	Worst	-	-	-	-	-	Assumption (Base+10%)	Assumption (Base+10%)	-
Unplanned Downtime	Best	Author Estimate (Base-28%)	-	Author Estimate (Worst-50%)	Assumption: -25%	-	Firm Employee	Firm Employee	-
	Base	Firm Employee	Firm Employee	Author Estimate (Worst-25%)	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Author Assumption
	Worst	Author Estimate (Base+29%)	-	Firm Employee	Assumption: +25%	-	Firm Employee	Firm Employee	-
Planned Downtime	Best	Firm Employee	-	-	Firm Employee	-	Firm Employee	Firm Employee	Assumption: -50%
	Base	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee
	Worst	Firm Employee	-	-	Firm Employee	-	Firm Employee	Firm Employee	Assumption: +50%

Fig. 2. This table lists the assumptions and sources of inputs in the model.

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		Coat A 1	Coat A 2	Coat A Prep	Coat B 1	Coat B Prep	Consolidation 1	Consolidation 2	Consolidation Prep
Energy Usage: Up	**Best**	Assumed Equal to Similar Equipment Specifications	Assumed Equal to Similar Equipment Specifications	-	Assumption: -5%	-	Assumption: -10%	Assumption: -10%	Assumption (Base-33%)
	Base	Assumed Equal to Similar Equipment Specifications	Assumed Equal to Similar Equipment Specifications	Author Assumption	Estimate from Equipment Specifications [B]	Author Assumption	Firm Data	Firm Data	Estimate from Equipment Specifications [D]
	Worst	Assumed Equal to Similar Equipment Specifications	Assumed Equal to Similar Equipment Specifications	-	Assumption: +5%	-	Assumption: +10%	Assumption: +10%	Assumption (Base+33%)
Maintenance Costs (Annual)	**Best**	-	-	-	-	-	-	-	-
	Base	Assumption: See Equations	Assumption: See Equations	Assumption: See Equations	Assumption: See Equations	Assumption: See Equations	Assumption: See Equations	Assumption: See Equations	Assumption: See Equations
	Worst	-	-	-	-	-	-	-	-
Reject Rate	**Best**	Author Estimate based on Firm Data	Author Estimate based on Firm Data	Author Estimate based on Firm Data	Author Estimate based on Firm Data	Author Estimate based on Firm Data	Author Estimate based on Firm Data	Author Estimate based on Firm Data	Author Estimate based on Firm Data
	Base	Author Estimate based on Firm Data	Author Estimate based on Firm Data	Author Estimate based on Firm Data	Author Estimate based on Firm Data	Author Estimate based on Firm Data	Author Estimate based on Firm Data	Author Estimate based on Firm Data	Author Estimate based on Firm Data
	Worst	Author Estimate based on Firm Data	Author Estimate based on Firm Data	Author Estimate based on Firm Data	Author Estimate based on Firm Data	Author Estimate based on Firm Data	Author Estimate based on Firm Data	Author Estimate based on Firm Data	Author Estimate based on Firm Data

Fig. 3. This table lists the assumptions and sources of inputs in the model.

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		Forming 1	Forming 2	Forming 3	Forming Prep	Grind A 1	Grind A 2	Grind A 3	Grind B 1	Grind B 2
Cycle Time	Best	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee
	Base	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee
	Worst	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee
Load/Unload Time	Best	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Assumption: -20%	Firm Employee	Firm Employee	Firm Employee
	Base	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee
	Worst	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Assumption: +33%	Firm Employee	Firm Employee	Firm Employee
Changeover Times, Yields (Product Specific)	Best	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee
	Base	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee
	Worst	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee
Main Machine Floorspace	Best	Assumption: -10%	Assumption: -10%	Assumption: -10%	Assumption: -20%	-	-	-	-	-
	Base	Estimate based on engineering drawings	Estimate based on engineering drawings	Estimate based on engineering drawings	Estimate	Estimate based on engineering drawings	Estimate based on engineering drawings	Estimate based on engineering drawings	Assumption based on similarly sized equipment	Assumption based on similarly sized equipment
	Worst	Assumption: +10%	Assumption: +10%	Assumption: +10%	Assumption: +20%	-	-	-	-	-
Batch Size/Shift Throughput	Best	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	-	-
	Base	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee
	Worst	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	-	-
Main Machine Price	Best	Estimate based on Historical Asset Costs	Estimate based on Historical Asset Costs	Estimate based on Historical Asset Costs	Assumption: -10%	Estimate based on Historical Asset Costs	-	Estimate based on Historical Asset Costs	Estimate based on Historical Asset Costs	Estimate based on Historical Asset Costs
	Base	Estimate based on Historical Asset Costs	Estimate based on Historical Asset Costs	Estimate based on Historical Asset Costs	Firm Employee	Estimate based on Historical Asset Costs	Estimate based on Historical Asset Costs	Estimate based on Historical Asset Costs	Estimate based on Historical Asset Costs	Estimate based on Historical Asset Costs
	Worst	Estimate based on Historical Asset Costs	Estimate based on Historical Asset Costs	Estimate based on Historical Asset Costs	Assumption: +10%	Estimate based on Historical Asset Costs	-	Estimate based on Historical Asset Costs	Estimate based on Historical Asset Costs	Estimate based on Historical Asset Costs
Fraction of Labor	Best	-	Firm Employee	Firm Employee	Firm Employee	Firm Employee	-	-	Firm Employee	Firm Employee
	Base	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee
	Worst	-	Firm Employee	Firm Employee	Firm Employee	Firm Employee	-	-	Firm Employee	Firm Employee
Labor: Burdened Wage	Best	-	-	-	-	-	-	-	-	-
	Base	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee
	Worst	-	-	-	-	-	-	-	-	-
Labor Dedication	Best	-	-	-	-	-	-	-	-	-
	Base	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee
	Worst	-	-	-	-	-	-	-	-	-
Material Type	Best	-	-	-	-	-	-	-	-	-
	Base	Firm Employee	Firm Employee	Firm Employee	-	-	-	-	-	-
	Worst	-	-	-	-	-	-	-	-	-

Fig. 4. This table lists the assumptions and sources of inputs in the model.

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Accepted manuscript posted November 09, 2018. doi:10.1115/1.4041943

		Forming 1	Forming 2	Forming 3	Forming Prep	Grind A 1	Grind A 2	Grind A 3	Grind B 1	Grind B 2
Material Use Rate	Best	-	-	-	-	-	-	-	-	-
	Base	Firm Employee	Firm Employee	Firm Employee	-	-	-	-	-	-
	Worst	-	-	-	-	-	-	-	-	-
Tooling Price	Best	Firm Employee	Firm Employee	Firm Employee	Attributed to Forming, not Prep	Author Assumption (Base-20%)	Author Assumption (Base-20%)	-	-	-
	Base	Firm Employee	Firm Employee	Firm Employee	Attributed to Forming, not Prep	Assuming Same as Similar Equipment	Assuming Same as Similar Equipment	Firm Employee	Firm Employee	Firm Employee
	Worst	Firm Employee	Firm Employee	Firm Employee	Attributed to Forming, not Prep	Author Assumption (Base+15%)	Author Assumption (Base+15%)	-	-	-
Replacement Rate	Best	Firm Employee	Firm Employee	Firm Employee	Attributed to Forming, not Prep	-	-	-	-	-
	Base	Firm Employee	Firm Employee	Firm Employee	Attributed to Forming, not Prep	Firm Employee	Assuming Same as Similar Equipment	Firm Employee	Firm Employee	Firm Employee
	Worst	Firm Employee	Firm Employee	Firm Employee	Attributed to Forming, not Prep	-	-	-	-	-
Auxiliary Equipment Price	Best	Assumption (Base-10%)	Assumption (Base-10%)	Assumption (Base-10%)	Assumption	-	-	-	-	-
	Base	Firm Data	Firm Data	Firm Data	Firm Data	Firm Data	Firm Data	Firm Data	Firm Data	Firm Data
	Worst	Assumption (Base+10%)	Assumption (Base+10%)	Assumption (Base+10%)	Assumption	-	-	-	-	-
Unplanned Downtime	Best	Firm Employee	Firm Employee	Firm Employee	Firm Employee	-	-	Firm Employee	Firm Employee	Firm Employee
	Base	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee
	Worst	Firm Employee	Firm Employee	Firm Employee	Firm Employee	-	-	Firm Employee	Firm Employee	Firm Employee
Planned Downtime	Best	Firm Employee	Firm Employee	Firm Employee	Firm Employee	-	-	-	-	-
	Base	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee
	Worst	Assumption: +100%	Assumption: +100%	Firm Employee	Firm Employee	-	-	-	-	-

Fig. 5. This table lists the assumptions and sources of inputs in the model.

Journal of Mechanical Design. Received April 24, 2018;
Accepted manuscript posted November 09, 2018. doi:10.1115/1.4041943

		Forming 1	Forming 2	Forming 3	Forming Prep	Grind A 1	Grind A 2	Grind A 3	Grind B 1	Grind B 2
Energy Usage: Up	Best	Assumed Equal to Similar Equipment	Assumed Equal to Similar Equipment	Estimate from Equipment Specifications [C]	-	Assumption: -50%	Assumption: -50%	Assumption: -10%	Assumption: -10%	Assumed Equal to Similar Equipment
	Base	Assumed Equal to Similar Equipment	Assumed Equal to Similar Equipment	Estimate from Equipment Specifications [C]	Author Assumption	Estimate from Equipment Specifications [F]	Estimate from Equipment Specifications [F]	Assumed Equal to Similar Equipment	Estimate from Equipment Specifications [H]	Assumed Equal to Similar Equipment
	Worst	Assumed Equal to Similar Equipment	Assumed Equal to Similar Equipment	Estimate from Equipment Specifications [C]	-	Assumption: +50%	Assumption: +50%	Assumption: +10%	Assumption: +10%	Assumed Equal to Similar Equipment
Maintenance Costs (Annual)	Best	-	-	-	-	-	-	-	-	-
	Base	Assumption: See Equations	Assumption: See Equations	Assumption: See Equations	Assumption: See Equations	Assumption: See Equations	Assumption: See Equations	Assumption: See Equations	Assumption: See Equations	Assumption: See Equations
	Worst	-	-	-	-	-	-	-	-	-
Reject Rate	Best	Author Estimate based on Firm Data	Author Estimate based on Firm Data	Author Estimate based on Firm Data	-	Author Estimate based on Firm Data	Author Estimate based on Firm Data	Author Estimate based on Firm Data	Author Estimate based on Firm Data	Author Estimate based on Firm Data
	Base	Author Estimate based on Firm Data	Author Estimate based on Firm Data	Author Estimate based on Firm Data	Assumption	Author Estimate based on Firm Data	Author Estimate based on Firm Data	Author Estimate based on Firm Data	Author Estimate based on Firm Data	Author Estimate based on Firm Data
	Worst	Author Estimate based on Firm Data	Author Estimate based on Firm Data	Author Estimate based on Firm Data	-	Author Estimate based on Firm Data	Author Estimate based on Firm Data	Author Estimate based on Firm Data	Author Estimate based on Firm Data	Author Estimate based on Firm Data
Scrap Rate (Plant Wide)	Best				Assumption (Base-10%)					
	Base				Firm Employee					
	Worst				Assumption (Base+10%)					

Fig. 6. This table lists the assumptions and sources of inputs in the model.

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		Inspection	Polish 1	Shaping 1	Shaping 2	Shaping 3	Ship	Surface Treatment 1	Surface Treatment 2	Wash 1
Cycle Time	Best	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee
	Base	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee
	Worst	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee
Load/Unload Time	Best	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	-	Firm Employee	Firm Employee	-
	Base	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee
	Worst	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	-	Firm Employee	Firm Employee	-
Changeover Times, Yields (Product Specific)	Best	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	-
	Base	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee
	Worst	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	-
Main Machine Floorspace	Best	Author Estimate	-	-	-	-	Author Estimate	-	-	-
	Base	Author Estimate	Assumption based on similarly sized equipment	Estimate based on engineering drawings	Estimate based on engineering drawings	Estimate based on engineering drawings	Author Estimate	Estimate based on engineering drawings	Estimate based on engineering drawings	Estimate based on engineering drawings
	Worst	Author Estimate	-	-	-	-	Author Estimate	-	-	-
Batch Size/Shift Throughput	Best	Author Estimate (Base+20% - Throughput)	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee
	Base	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee
	Worst	Author Estimate (Base-20% - Throughput)	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee
Main Machine Price	Best	Estimate based on Historical Asset Costs	Estimate based on Historical Asset Costs	Estimate based on Historical Asset Costs	Estimate based on Historical Asset Costs	Estimate based on Historical Asset Costs	Assumption (Base-10%)	Estimate based on Historical Asset Costs	-	-
	Base	Estimate based on Historical Asset Costs	Estimate based on Historical Asset Costs	Estimate based on Historical Asset Costs	Estimate based on Historical Asset Costs	Estimate based on Historical Asset Costs	Estimate based on Historical Asset Costs	Estimate based on Historical Asset Costs	Estimate based on Historical Asset Costs	Estimate based on Historical Asset Costs
	Worst	Estimate based on Historical Asset Costs	Estimate based on Historical Asset Costs	Estimate based on Historical Asset Costs	Estimate based on Historical Asset Costs	Estimate based on Historical Asset Costs	Assumption (Base+10%)	Estimate based on Historical Asset Costs	-	-
Fraction of Labor	Best	-	-	-	-	-	Firm Employee	Firm Employee	-	-
	Base	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee
	Worst	-	-	-	-	-	Firm Employee	Firm Employee	-	-
Labor: Burdened Wage	Best	-	-	-	-	-	-	-	-	-
	Base	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee
	Worst	-	-	-	-	-	-	-	-	-
Labor Dedication	Best	-	-	-	-	-	-	-	-	-
	Base	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee
	Worst	-	-	-	-	-	-	-	-	-
Material Type	Best	-	-	-	-	-	-	-	-	-
	Base	-	-	-	-	-	-	-	-	-
	Worst	-	-	-	-	-	-	-	-	-

Fig. 7. This table lists the assumptions and sources of inputs in the model.

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		Inspection	Polish 1	Shaping 1	Shaping 2	Shaping 3	Ship	Surface Treatment 1	Surface Treatment 2	Wash 1
Material Use Rate	Best	-	-	-	-	-	-	-	-	-
	Base	-	-	-	-	-	-	-	-	-
	Worst	-	-	-	-	-	-	-	-	-
Tooling Price	Best	-	Firm Employee	Firm Employee	Firm Employee	Firm Employee	-	Firm Employee	Firm Employee	-
	Base	Author Estimate	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Author Estimate	Firm Employee	Firm Employee	Author Estimate
	Worst	-	-	Author Estimate (Base+45%)	Author Estimate (Base+45%)	Author Estimate (Base+45%)	-	Author Estimate	Author Estimate (Base+13%)	-
Replacement Rate	Best	-	-	-	-	-	-	Firm Employee	-	-
	Base	Author Estimate	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Author Estimate	Firm Employee	Firm Employee	Author Estimate
	Worst	-	-	-	-	-	-	Firm Employee	-	-
Auxiliary Equipment Price	Best	-	-	-	-	-	-	-	-	-
	Base	Firm Data	Firm Data	Firm Data	Firm Data	Firm Data	Firm Data	Firm Data	Firm Data	Firm Data
	Worst	-	-	-	-	-	-	-	-	-
Unplanned Downtime	Best	-	Firm Employee	Firm Employee	-	Firm Employee	-	-	Author Assumption (Base-25%	-
	Base	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee
	Worst	-	Firm Employee	Firm Employee	-	Firm Employee	-	-	Author Assumption (Base+25%	-
Planned Downtime	Best	-	-	-	-	-	-	-	-	Firm Employee
	Base	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee	Firm Employee
	Worst	-	-	-	-	-	-	-	-	Firm Employee

Fig. 8. This table lists the assumptions and sources of inputs in the model.

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		Inspection	Polish 1	Shaping 1	Shaping 2	Shaping 3	Ship	Surface Treatment 1	Surface Treatment 2	Wash 1
Energy Usage: Up	Best	-	Assumed Equal to Similar Equipment	Assumption: -10%	Assumption: -10%	Assumption: -10%	-	Assumption: -10%	Assumed Equal to Similar Equipment	Assumed Equal to Similar Equipment Specifications
	Base	Author Assumption	Assumed Equal to Similar Equipment	Estimate from Equipment Specifications [G]	Estimate from Equipment Specifications [G]	Estimate from Equipment Specifications [G]	Author Assumption	Estimate from Equipment Specifications [E]	Assumed Equal to Similar Equipment	Assumed Equal to Similar Equipment Specifications
	Worst	-	Assumed Equal to Similar Equipment	Assumption: +10%	Assumption: +10%	Assumption: +10%	-	Assumption: +10%	Assumed Equal to Similar Equipment	Assumed Equal to Similar Equipment Specifications
Maintenance Costs (Annual)	Best	-	-	-	-	-	-	-	-	-
	Base	Assumption: See Equations	Assumption: See Equations	Assumption: See Equations	Assumption: See Equations	Assumption: See Equations	Assumption: See Equations	Assumption: See Equations	Assumption: See Equations	Assumption: See Equations
	Worst	-	-	-	-	-	-	-	-	-
Reject Rate	Best	Author Estimate based on Firm Data	Author Estimate based on Firm Data	Author Estimate based on Firm Data	Author Estimate based on Firm Data	Author Estimate based on Firm Data	Author Estimate based on Firm Data	Author Estimate based on Firm Data	Author Estimate based on Firm Data	Author Estimate based on Firm Data
	Base	Author Estimate based on Firm Data	Author Estimate based on Firm Data	Author Estimate based on Firm Data	Author Estimate based on Firm Data	Author Estimate based on Firm Data	Author Estimate based on Firm Data	Author Estimate based on Firm Data	Author Estimate based on Firm Data	Author Estimate based on Firm Data
	Worst	Author Estimate based on Firm Data	Author Estimate based on Firm Data	Author Estimate based on Firm Data	Author Estimate based on Firm Data	Author Estimate based on Firm Data	Author Estimate based on Firm Data	Author Estimate based on Firm Data	Author Estimate based on Firm Data	Author Estimate based on Firm Data

Fig. 9. This table lists the assumptions and sources of inputs in the model.

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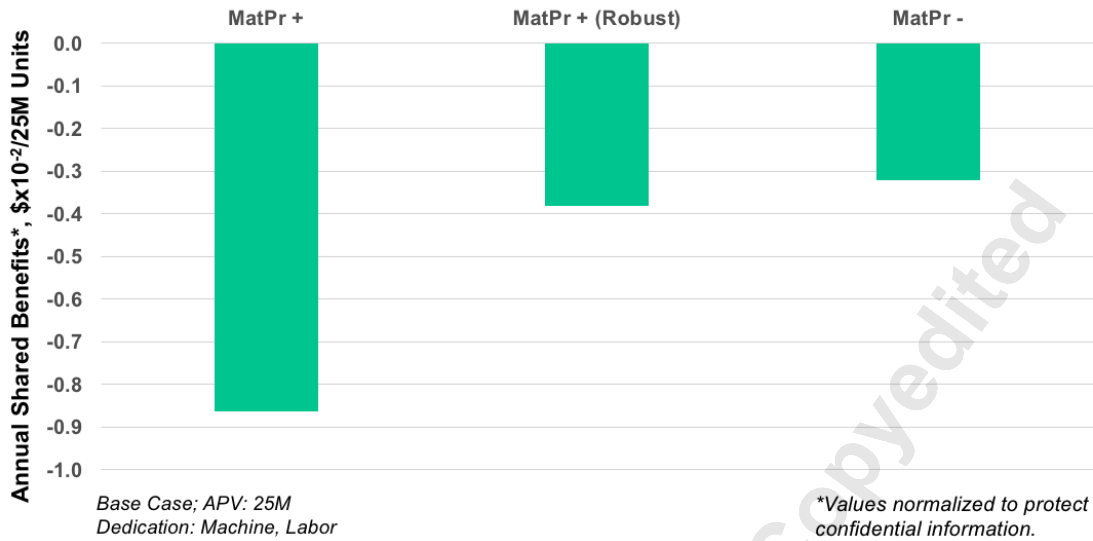

Fig. 10. Robustness check comparing the high volume robust material(+) with the original DOE selections.

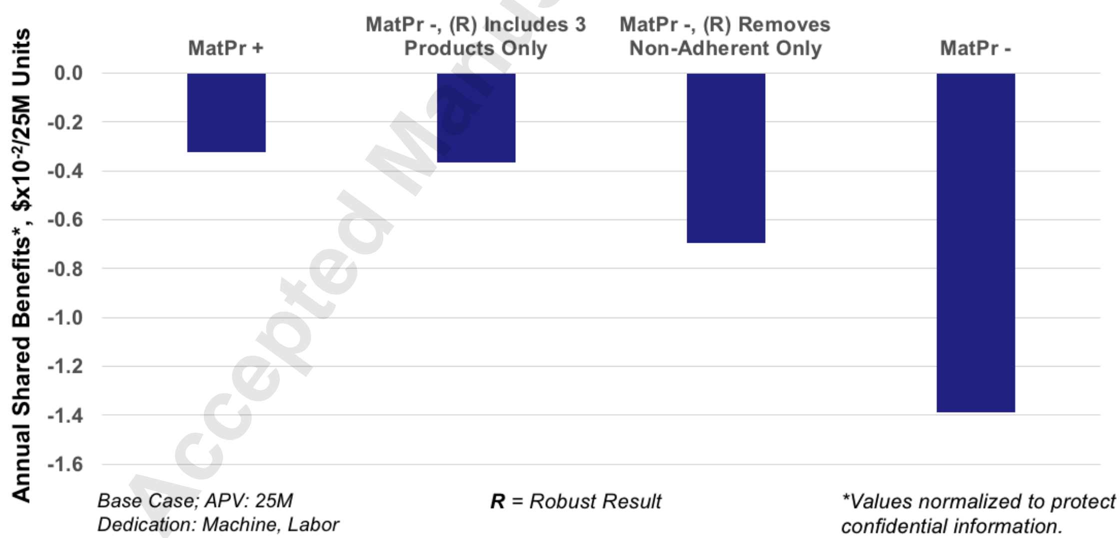

Fig. 11. Robustness check comparing the extreme robust material(-) with the original DOE selections.

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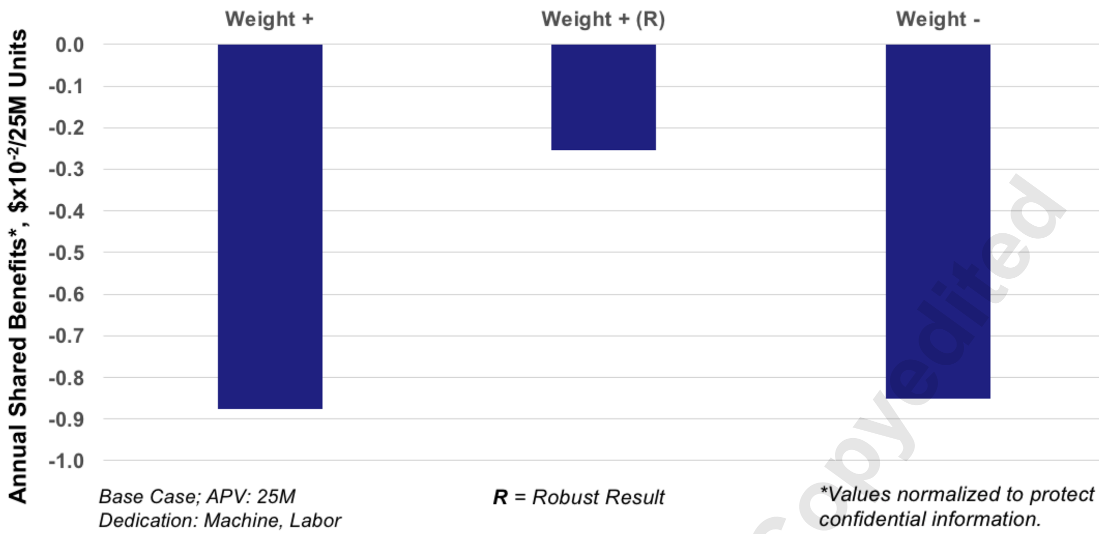

Fig. 12. Robustness check comparing the extreme weight(+) with the original extreme DOE selections.

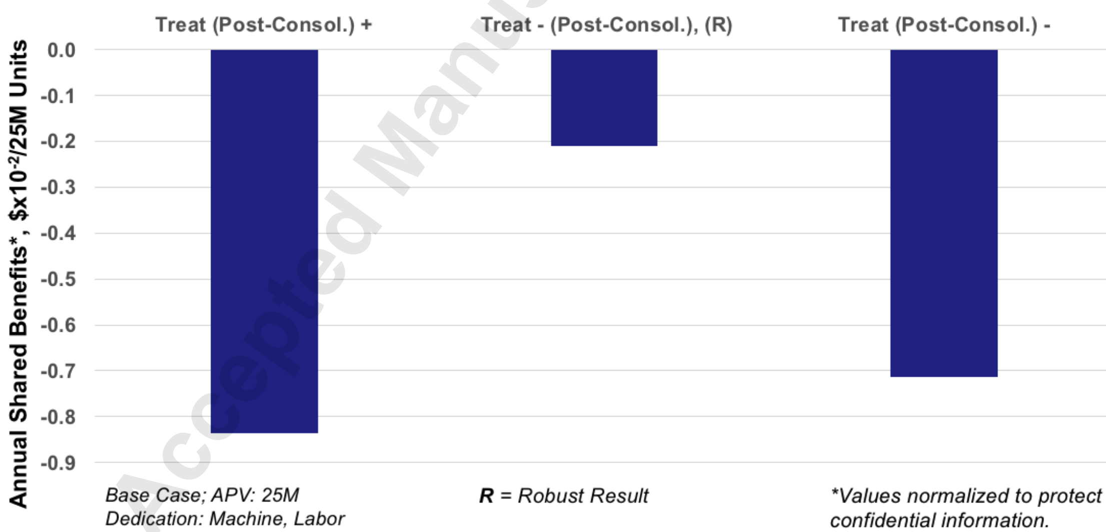

Fig. 13. Robustness check comparing the extreme robust treat(+) with the original extreme DOE selections.

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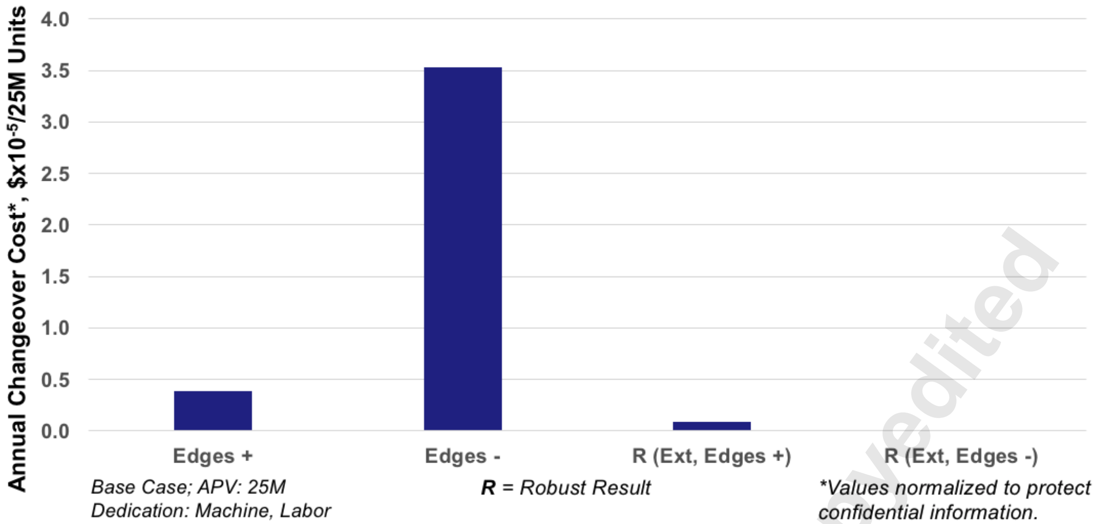

Fig. 14. Robustness check comparing the extreme robust edge(+) and edge(-) with the original extreme DOE selections.

	% Cost Reduction with Flexible Equipment:	
Equipment Type:	**Extreme**	**High Volume**
Base	-	-
Forming	2.1%	4.6%
Shaping	0.4%	-
Consolidation	0.6%	1.5%
Grind B	0.8%	-
Coating A	-	1.8%
All	3.9%	7.8%

Fig. 15. We find the percent reduction in total annual cost for the "All" (high-variety) mixes in the high-volume and extreme DOEs. Cells marked with a "-" indicate that flexible equipment does not apply to that mix, either because it is already implemented, or because the mix does not use it.

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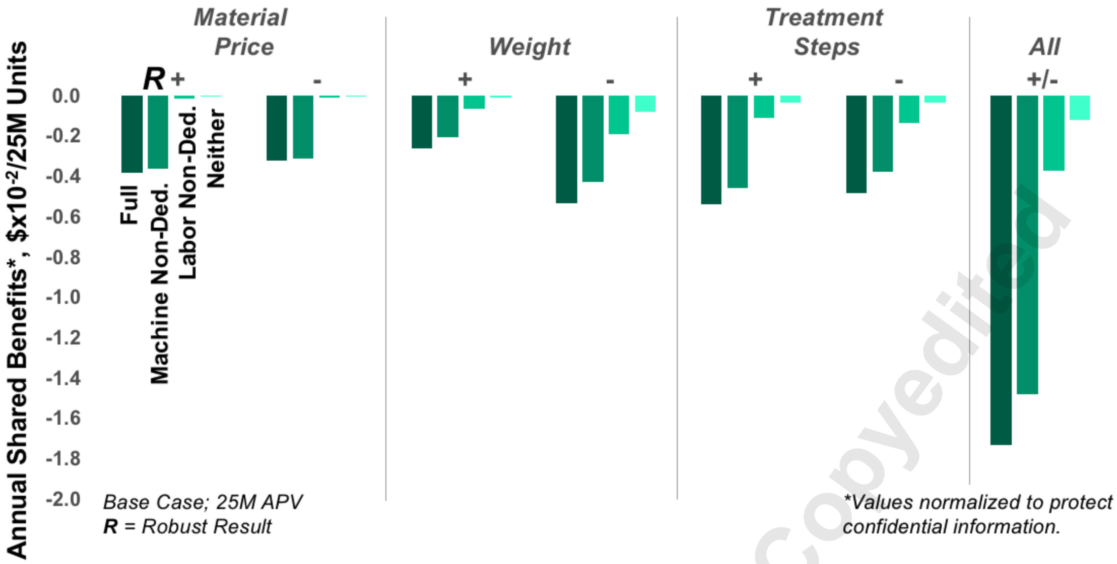

Fig. 16. As dedication levels are reduced, eliminating equipment and labor dedication, benefits disappear.

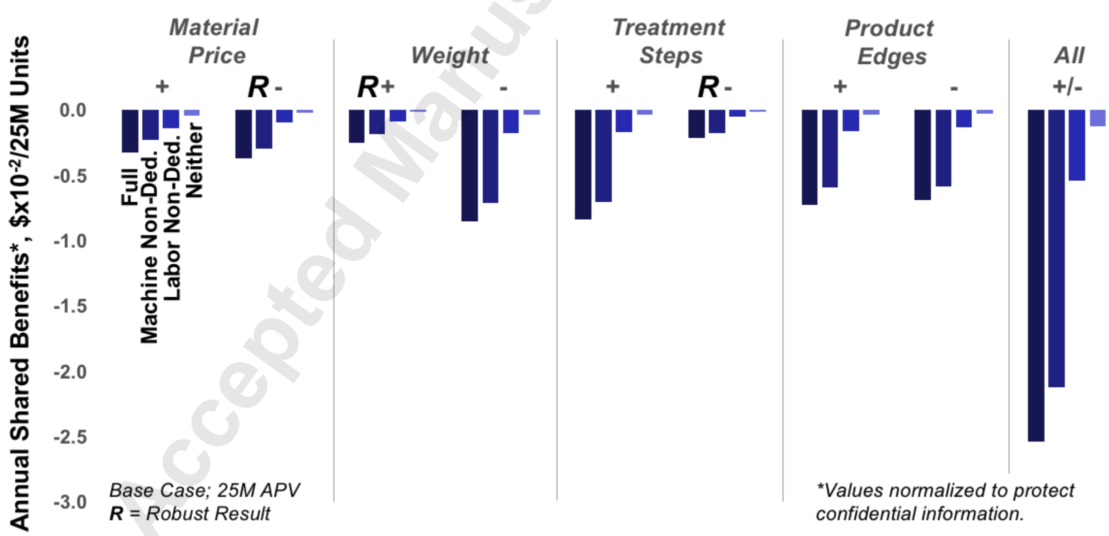

Fig. 17. As dedication levels are reduced, eliminating equipment and labor dedication, benefits disappear.

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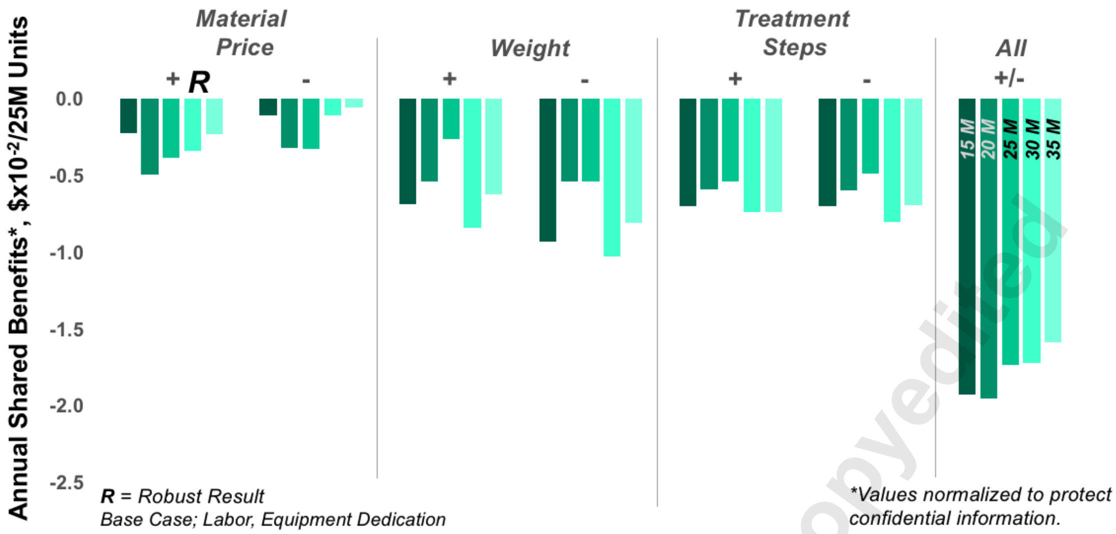

Fig. 18. Though there is variation in the exact level of shared benefits within attributes, generally, as APV increases from 15M to 35M parts, results hold.

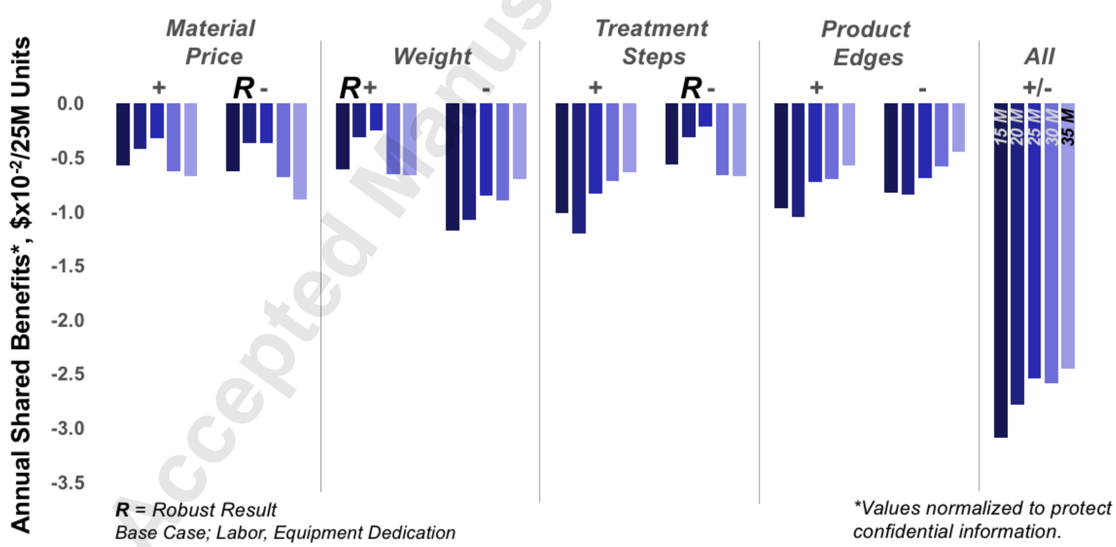

Fig. 19. Though there is variation in the exact level of shared benefits within attributes, generally, as APV increases from 15M to 35M parts, results hold.

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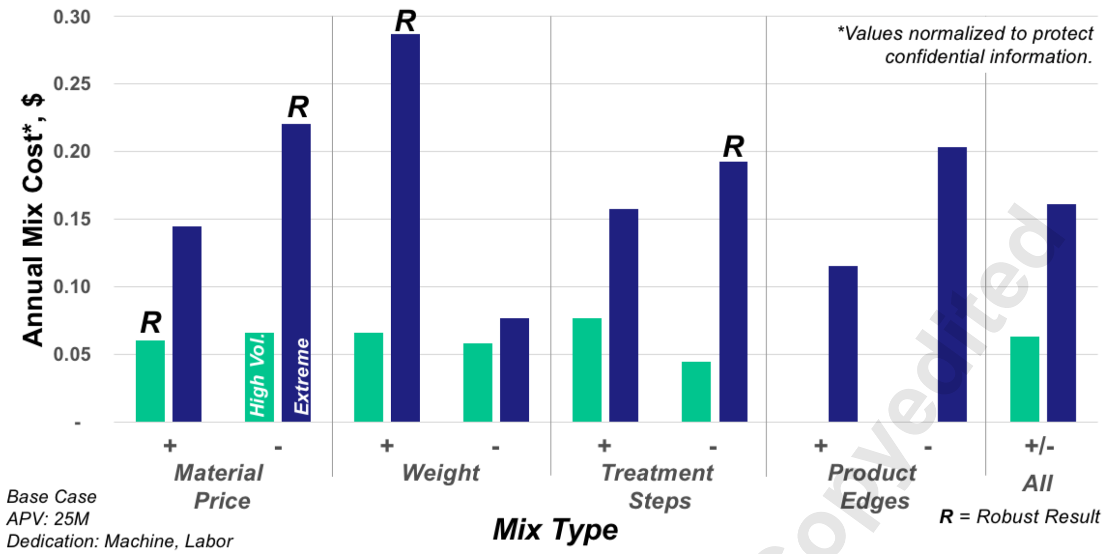
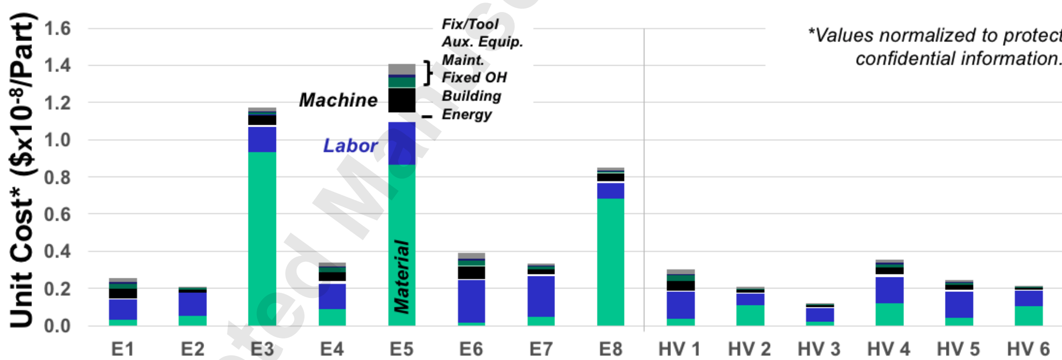


Fig. 20. There is a large difference in the annual mix costs between high-volume and extreme DOE. In the extreme DOE, weight appears to drive the difference between (+) and (-) annual mix costs.



	E1	E2	E3	E4	E5	E6	E7	E8	HV 1	HV 2	HV 3	HV 4	HV 5	HV 6
Material $	-	+	+	-	-	-	+	-	-	-	+	+	+	+
Weight	-	-	+	+	+	-	-	+	-	+	-	+	-	+
Treat	-	-	-	+	+	+	+	-	+	-	-	+	+	-
Edges	-	+	-	+	-	+	-	+						

Base Case, APV: 25M,
Dedication: Machine, Labor

Products: Extreme ***Products: High Volume***

Fig. 21. The unit costs indicate that labor and material are high portions of each product′s unit cost. Products with low weight have labor as a higher proportion of cost. Products with higher weight have material as a higher proportion of cost. Machine cost is the next-highest category, occasionally outweighing material cost in low-weight products

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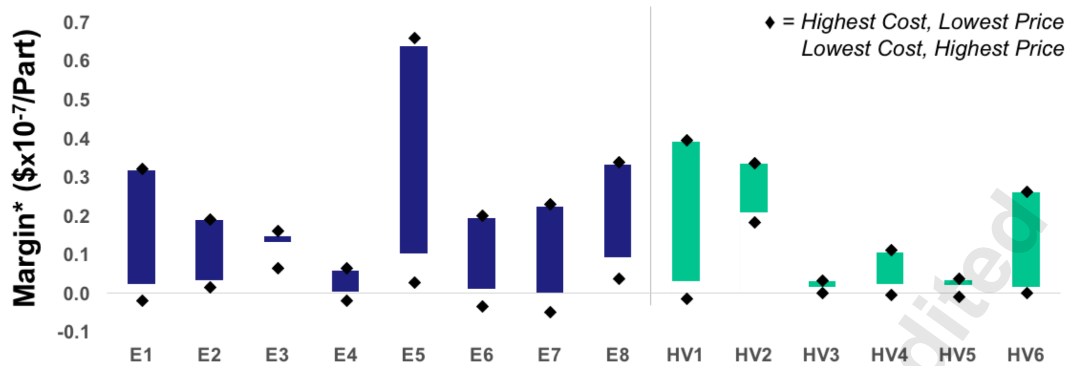

	E1	E2	E3	E4	E5	E6	E7	E8	HV1	HV2	HV3	HV4	HV5	HV6
Material $	-	+	+	-	-	-	+	-	-	-	+	+	+	+
Weight	-	-	+	+	+	-	-	+	-	+	-	+	-	+
Treat	-	-	-	+	+	+	+	-	+	-	-	+	+	-
Edges	-	+	-	+	-	+	-	+						

Base Case, APV: 25M, Dedication: Machine, Labor

Products: Extreme ***Products: High Volume***

**Values normalized to protect confidential information.*

Fig. 22. The unit margins indicate that most products have net-positive margins within the range of uncertainty in selling price. However, with cost uncertainties incorporated, some products appear to have possible net-negative margins

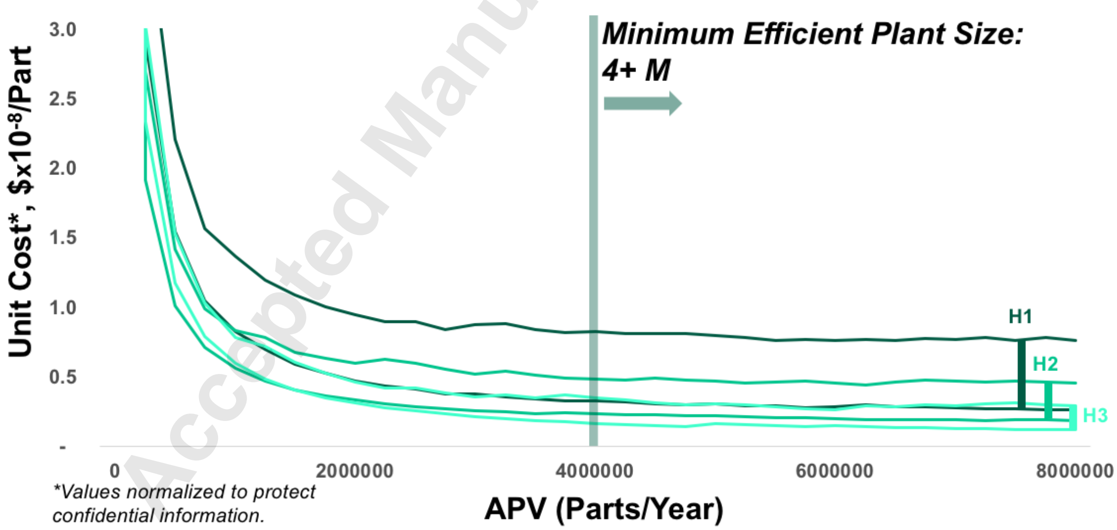

Fig. 23. This graph illustrates the best and worst case cost of products H1-H3 at a range of production volumes. We assume full dedication.

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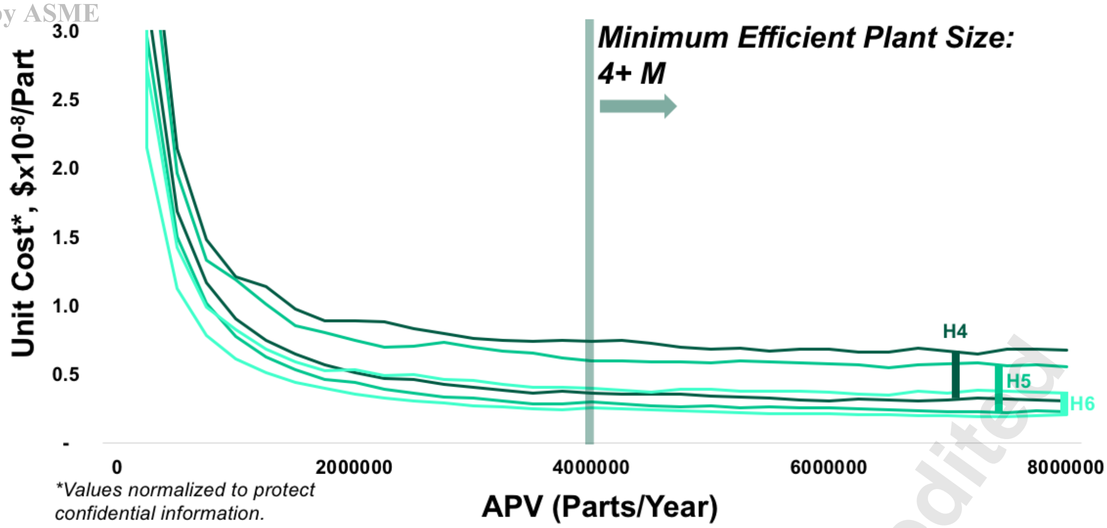

Fig. 24. This graph illustrates the best and worst case cost of products H4-H6 at a range of production volumes. We assume full dedication.

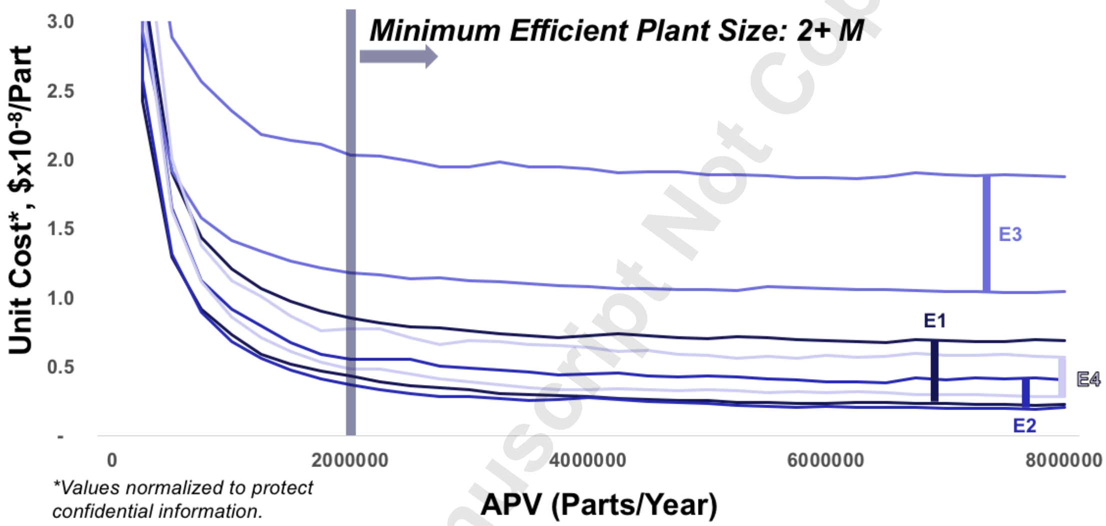

Fig. 25. This graph illustrates the best and worst case cost of products E1-E4 at a range of production volumes. We assume full dedication.

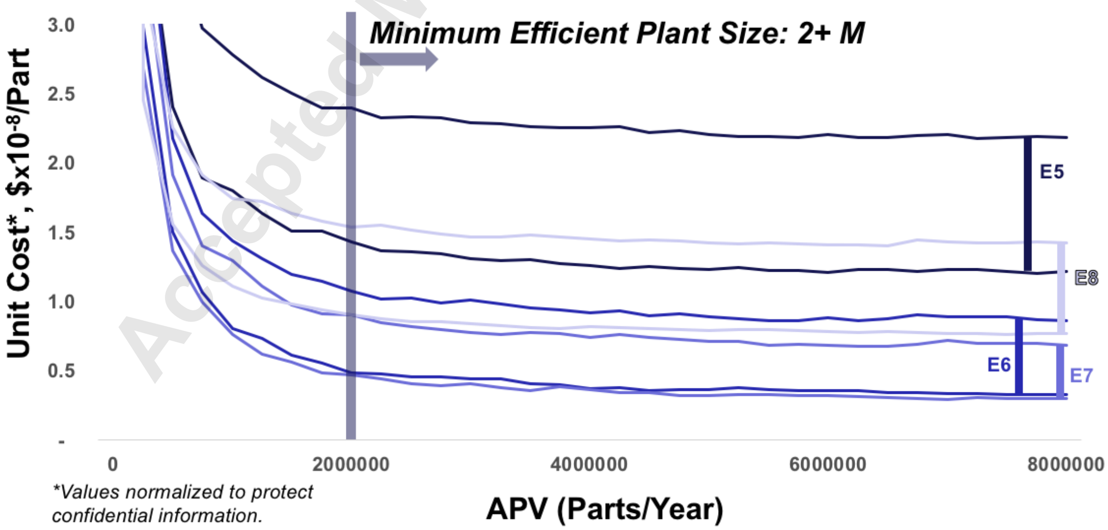

Fig. 26. This graph illustrates the best and worst case cost of products E5-E8 at a range of production volumes. We assume full dedication.

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	Weight: High Volume													
	Benefits ($x10^-4, Normalized)		Equipment Price ($x10^-4, Normalized)						Fraction of Labor (Operators)					
	+	-	Weight +			Weight -			Weight +			Weight -		
Coat A 1	-	-						45						0.3
Coat A 2	-	-				17						0.3		
Coat A Prep	-	-				2		2				1.1		1.1
Coat B 1	-	-		39						0.3				
Coat B Prep	-	-		-						1.0				
Consolidation 1	(4)	0	20	20	20			20	0.1	0.1	0.1			0.1
Consolidation 2	-	(9)				22	22					0.1	0.1	
Consolidation Prep	0	0	1	1	1	1	1	1	1.0	1.0	1.0	1.0	1.0	1.0
Forming 1	-	-												
Forming 2	0	-			9	9					0.3	0.3		
Forming 3	0	(5)	15	15			15	15	0.3	0.3			0.3	0.3
Forming Prep	(11)	(11)	1	1	1	1	1	1	1.0	1.0	1.0	1.0	1.0	1.0
Grind A 1	(6)	(6)	1	1	1	1	1	1	1.0	1.0	1.0	1.0	1.0	1.0
Grind B 2	-	-				10						0.3		
Shaping 1	0	(12)		4	4	4	4	4		2.0	2.0	2.0	2.0	2.0
Ship	-	-	3	3	3	3	3	3	2.5	2.5	2.5	2.5	2.5	2.5
Surface Treatment 1	-	-	1	1				1	0.5	0.5				0.5
Surface Treatment 2	-	-		6						1.0				
Wash 1	(5)	(10)	10	10	10	10	10	10	0.5	0.5	0.5	0.5	0.5	0.5

	Weight: Extreme															
	Benefits ($x10^-4, Normalized)		Equipment Price ($x10^-4, Normalized)							Fraction of Labor (Operators)						
	+	-	Weight + (R)			Weight -				Weight + (R)			Weight -			
Coat A 2	-	-					17	17	17					0.3	0.3	0.3
Coat A Prep	-	(6)					2	2	2					1.1	1.1	1.1
Coat B 1	-	-		39							0.3					
Coat B Prep	-	-		-							1.0					
Consolidation 1	(4)	(9)	20	20	20		20	20	20	0.1	0.1	0.1		0.1	0.1	0.1
Consolidation 2	-	-				22							0.1			
Consolidation Prep	-	(6)	1	1	1	1	1	1	1	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Forming 1	-	-	9		9					1.0		1.0				
Forming 2	-	-		9		9	9	9			0.3		0.3	0.3	0.3	
Forming 3	-	-							15							0.3
Forming Prep	(11)	(16)	1	1	1	1	1	1	1	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Grind A 1	-	(6)		1	1	1	1	1			1.0	1.0	1.0	1.0	1.0	
Grind A 2	-	-	1							1.0						
Grind A 3	-	-							7							1.0
Grind B 1	-	-						17							0.3	
Grind B 2	-	-				10							0.3			
Inspection	-	-							1							1.0
Polish 1	-	-														
Shaping 1	-	(12)		4		4	4	4			2.0		2.0	2.0	2.0	
Shaping 2	-	-	3							2.0						
Shaping 3	-	-							6							1.0
Ship	-	(15)	3	3	3	3	3	3	3	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Surface Treatment 1	-	-		1							0.5					
Surface Treatment 2	-	-		6				6			1.0				1.0	
Wash 1	(11)	(16)	10	10	10	10	10	10	10	0.5	0.5	0.5	0.5	0.5	0.5	0.5

Fig. 27. This shows heat maps for the weight attribute; more impactful values (whether greater cost reductions or greater factor inputs) are highlighted in darker colors. The extreme robust weight(+) and original design weight(-) attributes exhibit different levels of shared benefits, with robust weight(+) showing much lower benefits than weight(-). The extreme weight(+) DOE uses equipment that has higher labor for the forming step. The extreme weight(-) appears to derive greater sharing benefits from shared coating processes. The high-volume weight mixes each contain coating steps which cannot be shared.

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	Edges: Extreme																	
	Benefits ($\$x10^{-4}$, Normalized)		Equipment Price ($\$x10^{-4}$, Normalized)								Fraction of Labor (Operators)							
	+	-	Edges +				Edges -				Edges +				Edges -			
Coat A 2	-	-	17		17					17	0.3		0.3					0.3
Coat A Prep	-	-	2		2					2	1.1		1.1					1.1
Coat B 1	-	-		39					39			0.3					0.3	
Coat B Prep	-	-		-					-			1.0					1.0	
Consolidation 1	(9)	(4)	20	20	20	20		20	20	20	0.1	0.1	0.1	0.1		0.1	0.1	0.1
Consolidation 2	-	-					22								0.1			
Consolidation Prep	(6)	(6)	1	1	1	1	1	1	1	1	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Forming 1	-	-				9		9						1.0		1.0		
Forming 2	(5)	-	9	9	9		9		9		0.3	0.3	0.3		0.3		0.3	
Forming 3	-	-								15								0.3
Forming Prep	(16)	(16)	1	1	1	1	1	1	1	1	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Grind A 1	(12)	-	1	1	1	1	1		1		1.0	1.0	1.0	1.0	1.0		1.0	
Grind A 2	-	-						1								1.0		
Grind A 3	-	-								7								1.0
Grind B 1	-	-			17								0.3					
Grind B 2	-	-					10								0.3			
Inspection	-	-								1								1.0
Polish 1	-	-		2								1.0						
Shaping 1	-	(12)	4	4	4		4		4		2.0	2.0	2.0		2.0		2.0	
Shaping 2	-	-						3								2.0		
Shaping 3	-	-								6								1.0
Ship	(15)	(15)	3	3	3	3	3	3	3	3	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Surface Treatment 1	-	-		1					1			0.5					0.5	
Surface Treatment 2	-	-			6				6				1.0				1.0	
Wash 1	(11)	(16)	10	10	10	10	10	10	10	10	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5

Fig. 28. This shows a heat map for the (extreme only) edges attribute; more impactful values (whether greater cost reductions or greater factor inputs) are highlighted in darker colors. The edges heat map indicates that the edges(+) contains more shared processes than edges(-). It appears that edges(-) contains several shaping steps that are not able to be shared, each of which has high labor (shaping and grinding). Edges(+) contains several steps with high factor inputs (coating, use of only one consolidation technology) which are able to be shared, likely driving some of the benefits seen by edges(+).

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Material Price: High Volume

	Benefits ($x10^{-4}$, Normalized) +	Benefits ($x10^{-4}$, Normalized) -	Equipment Price ($x10^{-4}$, Normalized) MatPr + (R)		Equipment Price ($x10^{-4}$, Normalized) MatPr -		Fraction of Labor (Operators) MatPr + (R)		Fraction of Labor (Operators) MatPr -	
Coat A 1	-	-								
Coat A 2	-	-			17				0.3	
Coat A Prep	-	-			2				1.1	
Coat B 1	-	-		39				0.3		
Coat B Prep	-	-		-				1.0		
Consolidation 1	-	-		20		20		0.1		0.1
Consolidation 2	-	-	22		22		0.1		0.1	
Consolidation Prep	(5)	(5)	1	1	1	1	1.0	1.0	1.0	1.0
Forming 1	-	-								
Forming 2	-	-			9				0.3	
Forming 3	0	-	15	15		15	0.3	0.3		0.3
Forming Prep	(5)	(5)	1	1	1	1	1.0	1.0	1.0	1.0
Grind A 1	0	(6)	1	1	1	1	1.0	1.0	1.0	1.0
Grind B 2	-	-			10				0.3	
Shaping 1	(12)	-	4	4	4		2.0	2.0	2.0	
Ship	(16)	(16)	3	3	3	3	2.5	2.5	2.5	2.5
Surface Treatment 1	-	-		1		1		0.5		0.5
Surface Treatment 2	-	-		6				1.0		
Wash 1	-	-	10	10	10	10	0.5	0.5	0.5	0.5

Material Price: Extreme

	Benefits ($x10^{-4}$, Normalized) +	Benefits ($x10^{-4}$, Normalized) -	Equipment Price ($x10^{-4}$, Normalized) MatPr +			Equipment Price ($x10^{-4}$, Normalized) MatPr - (R)			Fraction of Labor (Operators) MatPr +			Fraction of Labor (Operators) MatPr - (R)		
Coat A 2	(7)	-	17		17		17		0.3		0.3		0.3	
Coat A Prep	-	-	2		2		2		1.1		1.1		1.1	
Coat B 1	-	-				39						0.3		
Coat B Prep	-	-				-						1.0		
Consolidation 1	(4)	(4)	20	20	20	20	20	20	0.1	0.1	0.1	0.1	0.1	0.1
Consolidation 2	-	-												
Consolidation Prep	-	-	1	1	1	1	1	1	1.0	1.0	1.0	1.0	1.0	1.0
Forming 1	-	-		9				9		1.0				1.0
Forming 2	-	(5)	9			9	9		0.3			0.3	0.3	
Forming 3	-	-			15						0.3			
Forming Prep	(11)	(11)	1	1	1	1	1	1	1.0	1.0	1.0	1.0	1.0	1.0
Grind A 1	-	-	1			1	1	1	1.0			1.0	1.0	1.0
Grind A 2	-	-		1						1.0				
Grind A 3	-	-			7						1.0			
Grind B 1	-	-					17						0.3	
Grind B 2	-	-												
Inspection	-	-			1						1.0			
Polish 1	-	-												
Shaping 1	-	(12)	4			4	4		2.0			2.0	2.0	
Shaping 2	-	-		3						2.0				
Shaping 3	-	-			6						1.0			
Ship	-	-	3	3	3	3	3	3	2.5	2.5	2.5	2.5	2.5	2.5
Surface Treatment 1	-	-				1						0.5		
Surface Treatment 2	-	-				6	6					1.0	1.0	
Wash 1	(11)	(5)	10	10	10	10	10	10	0.5	0.5	0.5	0.5	0.5	0.5

Fig. 29. This shows heat maps for the material attribute; more impactful values (whether greater cost reductions or greater factor inputs) are highlighted in darker colors. The extreme material(+) and robust extreme material(-) exhibit a wide diversity of treatment steps, reducing the benefits seen in either mix. The robust material(+) high-volume DOE exhibits higher exhibits higher benefits from sharing than the high-volume material(-) DOE. While our robustness check on this attribute indicated that the trend from (+) to (-) would stay the same, the gap in benefits shrinks between the two.

Journal of Mechanical Design. Received April 24, 2018;
Accepted manuscript posted November 09, 2018. doi:10.1115/1.4041943

Treatment: High Volume

	Benefits ($x10^-4, Normalized)		Equipment Price ($x10^-4, Normalized)						Fraction of Labor (Operators)					
	+	-	Treat +			Treat -			Treat +			Treat -		
Coat A 1	-	-			45						0.3			
Coat A 2	-	-	17						0.3					
Coat A Prep	(6)	-	2		2				1.1		1.1			
Coat B 1	-	-		39						0.3				
Coat B Prep	-	-		#						1.0				
Consolidation 1	0	(4)		20	20	20		20		0.1	0.1	0.1		0.1
Consolidation 2	0	-	22				22		0.1				0.1	
Consolidation Prep	0	-	1	1	1	1	1	1	1.0	1.0	1.0	1.0	1.0	1.0
Forming 1	-	-												
Forming 2	0	-	9					9	0.3					0.3
Forming 3	(5)	(5)		15	15	15	15			0.3	0.3	0.3	0.3	
Forming Prep	(11)	(11)	1	1	1	1	1	1	1.0	1.0	1.0	1.0	1.0	1.0
Grind A 1	(6)	(6)	1	1	1	1	1	1	1.0	1.0	1.0	1.0	1.0	1.0
Grind B 2	-	-	10						0.3					
Shaping 1	(12)	(12)	4	4	4		4	4	2.0	2.0	2.0		2.0	2.0
Ship	-	-	3	3	3	3	3	3	2.5	2.5	2.5	2.5	2.5	2.5
Surface Treatment 1	(3)	-		1	1	1				0.5	0.5	0.5		
Surface Treatment 2	-	-		6						1.0				
Wash 1	(10)	(10)	10	10	10	10	10	10	0.5	0.5	0.5	0.5	0.5	0.5

Treatment: Extreme

	Benefits ($x10^-4, Normalized)		Equipment Price ($x10^-4, Normalized)							Fraction of Labor (Operators)						
	+	-	Treat +				Treat - (R)			Treat +				Treat - (R)		
Coat A 2	-	-			17	17						0.3	0.3			
Coat A Prep	-	-			2	2						1.1	1.1			
Coat B 1	-	-	39	39						0.3	0.3					
Coat B Prep	(5)	-	#	#						1.0	1.0					
Consolidation 1	(9)	-	20	20	20	20		20	20	0.1	0.1	0.1	0.1		0.1	0.1
Consolidation 2	-	-					22							0.1		
Consolidation Prep	(6)	-	1	1	1	1	1	1	1	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Forming 1	-	-						9	9						1.0	1.0
Forming 2	(5)	-	9	9	9		9			0.3	0.3	0.3		0.3		
Forming 3	-	-				15							0.3			
Forming Prep	(16)	(11)	1	1	1	1	1	1	1	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Grind A 1	(6)	-	1	1	1		1		1	1.0	1.0	1.0		1.0		1.0
Grind A 2	-	-						1							1.0	
Grind A 3	-	-				7							1.0			
Grind B 1	-	-			17							0.3				
Grind B 2	-	-					10							0.3		
Inspection	-	-				1							1.0			
Polish 1	-	-	2							1.0						
Shaping 1	(12)	-	4	4	4		4			2.0	2.0	2.0		2.0		
Shaping 2	-	-						3							2.0	
Shaping 3	-	-				6							1.0			
Ship	(15)	-	3	3	3	3	3	3	3	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Surface Treatment 1	-	-	1	1						0.5	0.5					
Surface Treatment 2	-	-		6	6						1.0	1.0				
Wash 1	(11)	(11)	10	10	10	10	10	10	10	0.5	0.5	0.5	0.5	0.5	0.5	0.5

Fig. 30. We relate the process-level benefits for the treatment attribute to the major factor inputs for each process. More impactful values (whether greater cost reductions or greater factor inputs) are highlighted in darker colors. We find the mixes with high benefits are those that have more than one product using processes with high labor content and high equipment prices. The extreme treatment(-) included is a robust result.

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Accepted manuscript posted November 09, 2018. doi:10.1115/1.4041943

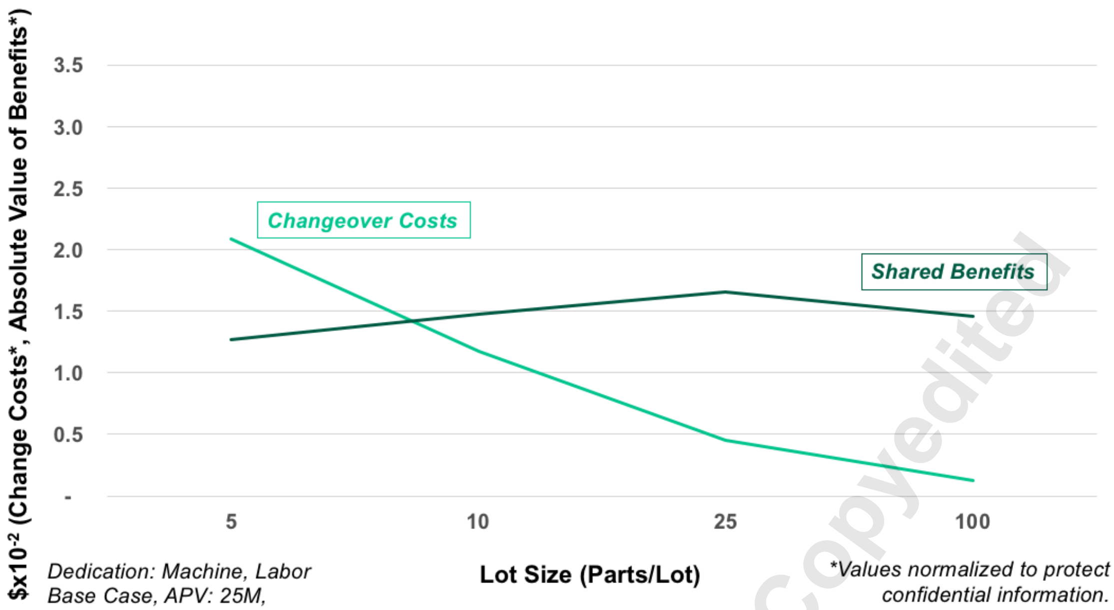

Fig. 31. This graph illustrates the lot sizes at which changeover costs outweigh shared benefits for the high volume "all" mix. Shared benefits are shown as absolute value (as opposed to their negative values shown in the results section) to better illustrate that crossover.

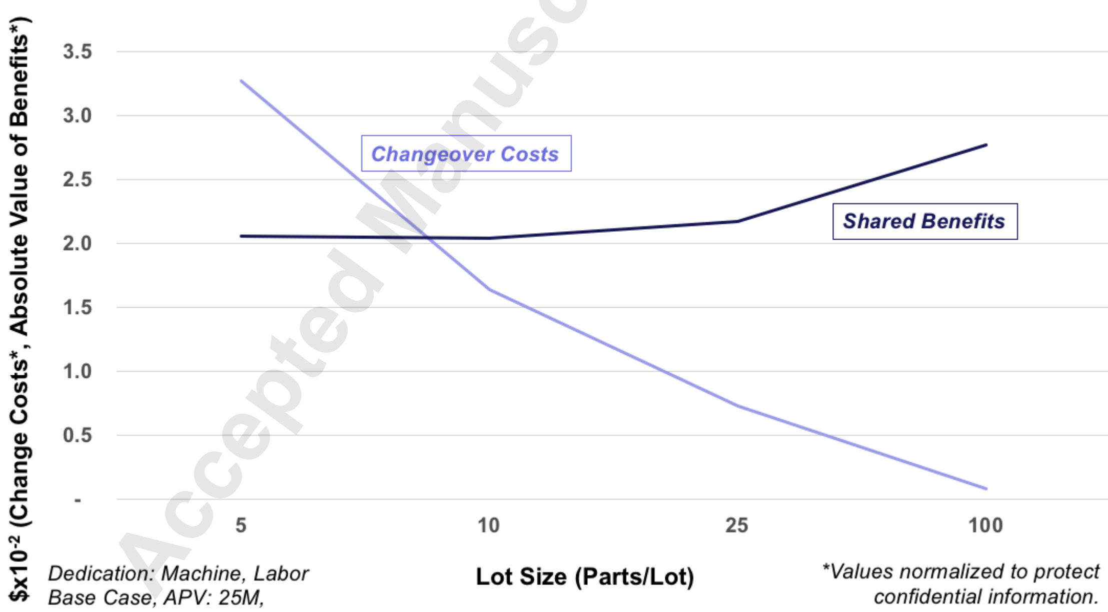

Fig. 32. This graph illustrates the lot sizes at which changeover costs outweigh shared benefits for the extreme "all" mix. Shared benefits are shown as absolute value (as opposed to their negative values shown in the results section) to better illustrate that crossover.