

An Analysis of Motor Vehicle Assembly Plant Complexity:
Developing a Framework to Evaluate the Existence of a Complexity Threshold
By

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Abstract

An automotive manufacturer facing decreasing average product volumes as a result of market fragmentation while simultaneously reducing its manufacturing plant footprint must adapt to the difficult challenge of increased product mix within its manufacturing system. The increase in complexity resulting from greater product mix is considered to be a significant driver in increasing plant investment cost and reducing plant operating effectiveness. Thus, the ability to fully understand and more effectively balance the complexity trade-offs associated with different product-to-manufacturing plant allocation scenarios is critically important, as the manufacturer formulates its strategy and analyzes the associated costs and benefits. The ultimate question to be addressed is whether there exists a “complexity threshold” in terms of the maximum number of differentiated body styles (unique vehicle models) to be produced inside a single assembly plant.

This thesis analyzes the challenge of manufacturing system and plant complexity by first developing a competitive benchmark study of body-style complexity at the major North American OEMs’ plants. Then, manufacturing and operations data is analyzed for evidence of a “complexity threshold” in one manufacturer’s operations. Finally, a linear-program based optimization model is developed to enable a Manufacturing Planning group to better understand the company’s tolerance for plant complexity by quantifying manufacturing costs associated with various product-to-manufacturing plant allocation scenarios. This tool enables the planner to simultaneously consider thousands of different possible combinations of which products to produce in which plants, by analyzing manufacturing investment and per-vehicle operating cost estimates for each combination. The ability to impose constraints on the maximum number of body styles produced at any one plant yields insight on the value of pursuing a higher-mix (in terms of body styles) manufacturing strategy in particular plants, or across the entire plant footprint.

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Most important, special thanks to my wife Randy, who has adapted to different jobs and environments – first at MIT, then in Michigan, then back at MIT as I pursued my education through the LFM program – her flexibility, support, and patience will be forever appreciated.

Biographical Note

A native of St. Louis, Missouri, Matthew J. Hasik graduated magna cum laude from Duke University in 1998, receiving his Bachelor of Science in Engineering degree with dual majors in Civil & Environmental Engineering and Public Policy Studies. He was commissioned an officer in the United States Navy, and entered active-duty service.

Matt was the recipient of both a Fulbright Scholarship and a Duke University Graduate School Fellowship, and earned his M.S. in Mechanical Engineering from Duke University in December 1999, completing a research program in the areas of acoustics and ultrasound. He was published in November 2002 as principal author of *Evaluation of Phospholipid Ultrasound Contrast Agents* in the journal *Ultrasonics*.

Matt completed the Navy's Surface Warfare Officers School in Newport, RI, and spent about two years onboard USS ELROD (FFG-55) in Norfolk Virginia as Main Propulsion Assistant. He qualified as Engineering Officer of the Watch, Officer of the Deck, and Surface Warfare Officer, and completed a deployment to the Mediterranean Sea as part of the Standing NATO Force Mediterranean following 9.11.01. He was selected as Destroyer Squadron Twenty-Eight's Shiphandler of the Year in 2001.

Matt then took a position at the Supervisor of Shipbuilding, Newport News, Virginia as Assistant Project Manager (Combat Systems) for the refueling and complex overhaul (RCOH) of USS DWIGHT D. EISENHOWER (CVN-69). During this time he qualified as an Engineering Duty Officer, including Docking Officer certification.

Matt left active-duty military service to pursue his MBA and Masters Degree in Engineering at the Massachusetts Institute of Technology, under the auspices of the Leaders for Manufacturing (LFM) Program. He completed a seven month internship at a major automotive manufacturer in their Manufacturing Planning and Advanced Vehicle Development groups, developing the research work described herein.

Matt is married to Dr. Randy Hasik of Seaside Park, NJ.

Introduction & Problem context

Increased competition, shifting customer preferences, and changing marketplace dynamics in the motor vehicle industry have led to increased product proliferation around the world, including North America, widely regarded as the most competitive among the major automotive markets. Responding to market trends in this highly competitive arena has forced the Original Equipment Manufacturers (OEMs), such as General Motors (GM), Ford, DaimlerChrysler (DCX), Toyota, and Honda, to increasingly offer more and more unique vehicles to suit a widening array of customer needs. Branching out beyond traditional sedans, wagons, and sports cars, OEMs began selling minivans and sport utility vehicles (SUVs) in the 1980s and 1990s, adding multiple truck-product entries (regular cab, extended cab, crew cab, short box, etc.), and rounding out their product offering with mid-size and small SUVs in the late 1990s. More recently, manufacturers have begun designing crossover utility vehicles (CUVs), essentially sport wagons built on car platforms.

From the customer's perspective, the trend has led to greatly increased consumer choice for both the function and styling of a desired vehicle. And while certain manufacturers have established first-to-market presence in particular new segments, the other OEMs typically quickly followed, bringing even further innovation, differentiation, and competitive prices with them in the rush to offer new and profitable products.

This trend has, however, presented a number of manufacturing challenges for the OEMs, especially in mature markets such as North America and Europe, as they have added new products proportionally faster than the overall rate of sales growth in the industry. The result has been the decrease in the average volume per vehicle body style produced and sold, as customer demand has spread across more product segments, more manufacturers, and more types of body styles. In fact, Pil and Holweg studied the European passenger car market from 1990-2002 and concluded just that (see Table 1 and Figure 1). The number of body styles offered in this mature market has doubled in this time period, while the average production volume per body style has fallen by nearly 50%, to just 69,000 units annually.¹

Given the relatively strong economies of scale which exist in the automotive industry, the challenge has been to meet market demand for different customer preferences without resorting to a manufacturing system that sacrificed these economies, while meeting increasingly stringent demands for high quality.

Table 1: Study of European Passenger Car Platforms, Body Styles, and Volumes (1990-2002)²

	1990	2002	Change 1990-2002 (%)
# Platforms produced (built in Europe)	60	46	-23.3
# Body styles offered (built in Europe)	88	179	+103.4
Average # body styles per platform	1.5	3.9	+160.0
Average production volume per platform (000s)	190	269	+41.6
Average production volume per body style (000s)	129	69	-46.5

¹ Pil and Holweg, p. 399.

² Pil and Holweg, p. 399.

Data reflects products built in Europe; does not include products built elsewhere but sold in Europe

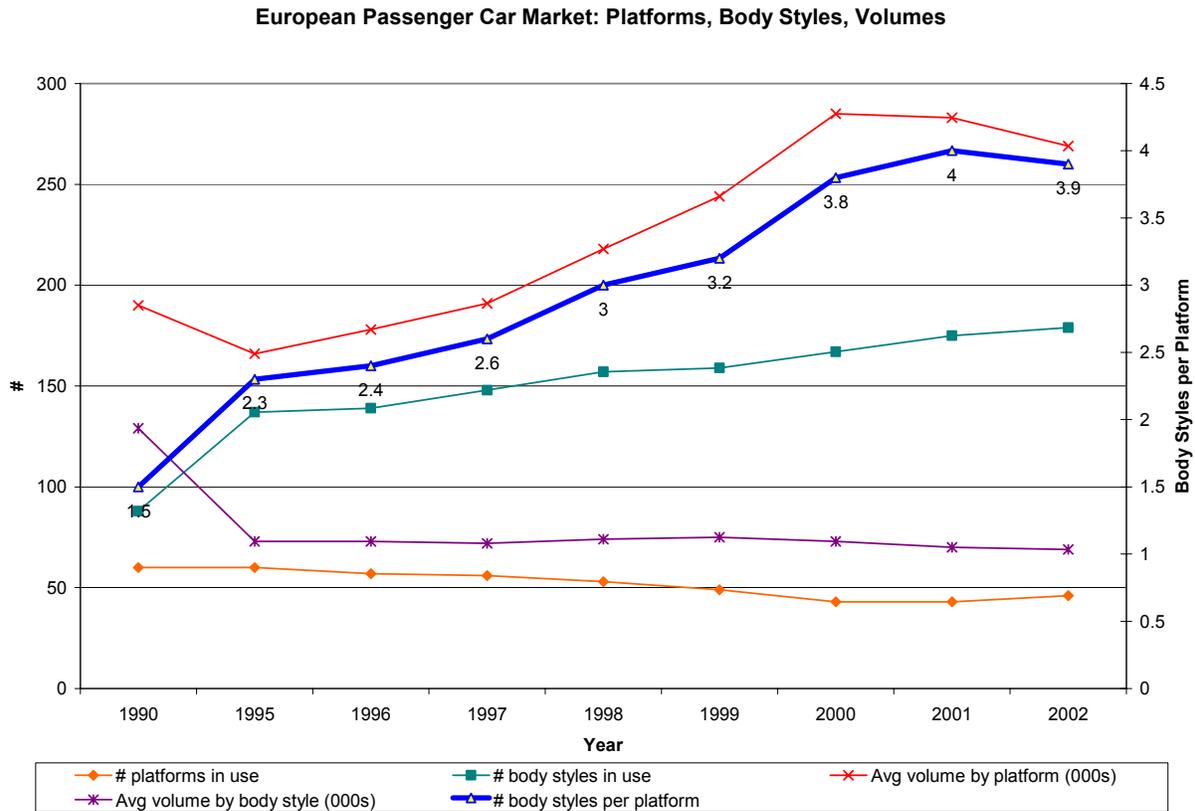


Figure 1: European Passenger Car Market: Platforms, Body Styles, and Volumes 1990-2002³

To accommodate the competing priorities of customer preference for vehicle variety and the market and manufacturer’s requirements for cost competitiveness, OEMs have long utilized a strategy of product platforms to varying degrees. Multiple products are designed based on the same key structures (platform or underbody), incorporating different body sides, top-level structure, and interiors to turn what is one set of major designs and components into multiple vehicles, for instance, a sedan, coupe, and convertible all based on the same underlying engineering and components. The key to this strategy is that not only can engineering costs be shared more widely across multiple vehicles, but manufacturing facilities can be designed based on this platform-sharing commonality.

The trend towards increased product proliferation and decreased average volumes seems only to be accelerating with the aforementioned wide introduction of car-based crossovers across OEMs. Thus, firms must critically evaluate their manufacturing strategy and determine how to adapt to these challenges, including a look at both the macro (across the entire enterprise of plants) and micro (inside a particular plant) levels.

A cost-effective manufacturing strategy typically attempts to drive plant utilization up towards or beyond 100% in order to achieve maximum scale economies, while minimizing manufacturing capital investment

³ Pil and Holweg, p. 399.

necessary to produce the required vehicles. This effort becomes even more critical when labor is considered a fixed cost due to the long term and relatively inflexible nature of contracts typical in the traditional auto industry. Ideally, a manufacturing facility would be able to produce a wide variety of different styles of vehicle, up to and beyond its volume capacity maximum, and thus easily satisfy the market's requirements, whether they be low-mix, high-volume or higher-mix, lower average volume manufacturing. (Note that product mix in this text refers to the number of different body styles or models produced by the manufacturing facility).

Flexibility plays a key role here, enabling the manufacturer to respond to two primary challenges. First, uncertainty in the marketplace for particular vehicles is mitigated by configuring the manufacturing system to be able to produce different types of vehicles, so that production can quickly be shifted, whether in the short (timeframe of weeks) or medium (timeframe of months) term to the correct product mix with minimal penalties in time, cost, and quality. Second, flexibility in the manufacturing system enables the firm to more easily and cost-effectively transition between generations of vehicles. In essence, flexibility is an "investment that creates options for the company".⁴ While flexibility plays a role in the evaluation of the manufacturing strategy necessary to achieve production of increasingly differentiated products, this text will not directly address the topic, as a wide body of literature exists on the subject. Instead, flexibility will only be addressed in terms of its relationship to and impact on manufacturing plant complexity.

Yet producing a wide array of products in a single facility presents significant challenges, many of which can be described by the term "complexity". For instance, designing a manufacturing system that is able to handle multiple unique parts that must be fitted to an assembly at the same point in the assembly sequence presents significant challenges in material flow and presentation, automated conveyance, scheduling, assembly time constraints, and labor skill. Designing machine tools that are able to manufacture multiple types of products leads to increasingly complicated fixturing and control systems. However, configuring a manufacturing plant to produce each unique product on a dedicated line with its own equipment, tooling, and labor can itself lead to system-level complexities and associated higher costs.

As a manufacturer strives to increase the number of vehicles it is producing in a single plant in order to meet customer demand for differentiated vehicles while balancing the need to achieve scale economies and minimize capital investment, it will experience increased assembly plant complexity. Complexity has been addressed in a wide variety of academic and business literature; several pertinent concepts are described in the following section.

Literature Review

A literature review was conducted in order to determine which previous work performed in the area of complexity analysis and management would be useful in guiding this study. These references were used to help frame the challenge of evaluating a manufacturing plant complexity threshold. The most pertinent are reviewed here.

Definitions of Complexity

First, the literature review focused on the definition of the word complexity, and how it relates to the manufacturing system. An excellent overview of several relevant definitions is developed by Sussman, who evaluated about twenty different texts.

⁴ Gerwin, p. 397.

Among these works, Joel Moses describes “complexity and flexibility” as “a system...composed of many parts interconnected in intricate ways...” and defines the “...complexity of a system simply as the number of interconnections between the parts.”⁵

Lovejoy and Sethuraman discuss “complexity costs” of performing a heterogeneous rather than homogeneous set of tasks. They state “...task variety alone, even absent time pressures, can cause direct quality problems. It is recognized in the human factors literature that managing a wider array of stimuli can decrease performance. These quality effects can impose rework that amplifies time pressures. Therefore, it can be difficult to untangle the effects of time-based and quality-based complexity phenomena, because behaviors will adjust to substitute one for the other.”⁶ Additionally, they point out that the cost of complexity can be seen through the concept of dis-economies of scope, the difference between performing heterogeneous and homogeneous tasks.

Ziegler’s thesis for the Ford Motor Company “*Complexity Reduction in Automotive Design and Development*” essentially comes to three conclusions; the first surrounding the use of design structure matrix (DSM) and axiomatic design concepts (ADC); the second concerning the existing management of information; and finally, the need to reduce complexity and complicatedness through reuse.⁷

His work focuses on how to apply DSM and ADC to product development in order to yield benefits of reduced complexity. A short case-study of complexity using a system dynamics model of the Ford Taurus reveals that simplification is achieved through re-use. Thus, sharing parts and engineering solutions (reuse) lowers manufacturing complexity.

Calinescu et al. define manufacturing complexity as a “systemic characteristic which integrates several key dimensions of the manufacturing environment which include size, variety, concurrency, objectives, information, variability, uncertainty, control, cost and value.” They note that process and equipment complexity drive costs higher because of the required flexibility in handling components or subassemblies of different shapes or configurations. Due to the differences in the number of components, additional assembly stations and floor space may be required, with the potential for low utilization at the facility. As a result, line balancing can be quite difficult. They summarize that some of the direct impacts of variety (in this case, increased product mix) on manufacturing are complexity in material processing, excessive capital investment, changes in assembly sequence, and complexity in line balancing.⁸

Saeed and Young define complexity in companies as the “...systemic effect that numerous products, customers, markets, processes, parts, and organizational entities have on activities, overhead structures, and information flows.” They believe the main problem triggered by excess complexity is the appearance of hidden costs, which are generally not visible and can negatively affect the competitive advantage of the enterprise.⁹

The challenge, as Blecker et al. point out, is to determine how much complexity is optimal.¹⁰ Saeed and Young propose to identify the complexity the customer rewards and the complexity for which the market is not willing to pay.¹¹ One might term the former “good complexity” and the latter “bad complexity”.

⁵ Sussman, p. 3.

⁶ Lovejoy and Sethuraman, p. 222-223.

⁷ Ziegler.

⁸ Calinescu, p. 1.

⁹ Saeed & Young, p. 1.

¹⁰ Blecker, et al.

These authors all point to several key themes in their research work on complexity:

- Sharing and re-use of resources reduces complexity
- Complexity arises due to the non-homogeneity of tasks to be performed
- Complexity has system or enterprise-wide effects that are not always seen nor well-understood

Product Variety, Option Variability, and Impact on Manufacturing Operations

There is a large body of research work focused on the automotive sector, much conducted under the auspices of the International Motor Vehicle Program affiliated with the Massachusetts Institute of Technology (MIT) over the last 15+ years. Several of these works have specific relevance here.

First, MacDuffie, Sethuraman, and Fisher's work of "*Product Variety and Manufacturing Performance: Evidence from the International Automotive Assembly Plant Study*" examines the effects of product variety on labor productivity and consumer-perceived quality measures. They conclude that the impact of product variety on manufacturing performance varies, and seems to be "much less than conventional manufacturing wisdom would predict".¹² They break product variety into several categories, including fundamental variety (model mix complexity: platforms, body styles, drivetrain configurations), intermediate variety (parts complexity: engine/transmission configurations, parts, percent shared parts, suppliers), and peripheral variety (option content, variability).

In particular, they found no statistically significant effect of their various measures of product variety (complexity) on product quality. They did find a consistent and negative relationship between parts complexity and labor productivity (higher complexity leading to lower productivity).¹³ This is revealing in that it agrees with conclusions drawn from other researchers (above) that using different assemblies increases complexity in vehicle manufacturing operations, and sharing or re-using parts and engineering solutions reduces complexity.

Further, MacDuffie et al. conclude that the presence of lean systems greatly enhances the ability of the manufacturing organization to adapt to and handle increased product complexity. In fact, they believe that investments in such systems can render handling increased variety and complexity "free", much as lean systems can yield quality improvements that are "free".¹⁴

There has been ongoing discussion among automotive industry professionals concerning the validity of using part counts (or cost-weighted part counts) vs. the number of build combinations as an indication of manufacturing plant and system complexity. Some argue that part counts are a better measure, as they may provide more insight on the total system costs, including design, development, manufacturing, logistics, etc. This may seem counter-intuitive, in that many on a first analysis would conclude that a greater number of possible combinations of the product's features would indicate just how complex the product, and therefore the manufacturing system, truly is. However, consider the following example.

A vehicle that offers power windows and aluminum wheels as "free-flow" options (ie, available on any vehicle regardless of option package selected) has 4 possible combinations (neither option, both options, or one of either options). A vehicle that offered those two options only as an "option package", i.e.,

¹¹ Saeed and Young, p. 2.

¹² MacDuffie, et al., p. 350.

¹³ MacDuffie, et. al, p. 362.

¹⁴ MacDuffie, et. al, p. 68.

bundled together, would only show two combinations (both installed, or neither installed). If one were to compare the number of combinations as a measure of the complexity in building that vehicle, he may conclude that the first vehicle is perhaps twice as complex as the second. Yet the vehicles have the same content (namely, power windows and aluminum wheels), and require basically the same amount of direct labor to install those options. In fact, the installation of the power window and the special wheel/tire set typically occurs at very different assembly stations inside the plant, and the workers performing these tasks are not affected by the presence or lack of the other item of vehicle content.

In fact, a simplistic view of combinations may not reveal the full impact of complexity on a plant's operations. A more detailed look at option variability within particular assembly stations is necessary. For instance, the variability in an assembly worker's installation of either a power window or a manual window (when installed at the same station) may have an impact not only on the particular station worker, but also on the plant's logistics and support structures that provide the correct array of parts for each vehicle. In fact, Fisher and Ittner argue that the introduction of option content variability into a plant makes planning and scheduling more complex, delivering parts to the line more difficult, and increases the chance of assembly errors, leading to higher overhead and rework requirements.¹⁵

MacDuffie et al. reported that option variability actually had a positive correlation with labor productivity. In other words, higher variability was associated in their study with higher productivity, not the outcome many would expect. The authors believe that this is due to the fact that plants which processed more highly variable products operated on a different, more flexible production frontier than did the others, and were perhaps less affected by such variability.¹⁶

Fisher and Ittner, in a somewhat more in-depth study of a single assembly plant, concluded that product variety, as seen through option variability, increases indirect costs (including overhead hours, rework, and inventory) and adds excess labor capacity at work stations (required as a buffer against variability). They determined that option variability does not affect direct labor significantly, as the assembly line tends to be buffered (provided with excess capacity) at the particular stations where variability is a real problem. However, that means the manufacturer is paying for this variability inherently in his overall industrial engineering design. While the results are limited to a single plant, the authors believe that their results suggest product mix variability is a better indicator of product variety in mixed-model assembly operations than measures such as part counts.¹⁷

Reducing option variability through option-package bundling reduces "external variety", as seen by the customer, helping firms to reduce forecast error and the obsolescence risk of inventory, as well as simplifying a product's choices for the customer. However, reducing external variety may not necessarily lead to a commensurate reduction in "internal variety" or complexity, as the content specified by these options still must be installed on the vehicle. If the OEM is able to install this content with lower variability, Fisher and Ittner's results would suggest that the OEM would reduce his indirect costs. Late-point configuration of vehicles may also reduce assembly complexity by taking parts out of the assembly plant, but other reasons to employ this strategy include more flexibly meeting customer requirements.¹⁸

It should be pointed out that Fisher and Ittner's work concluded that product variety is not a critical issue for the body shop and paint processes, as their automation and flexibility levels are adequate to handle the

¹⁵ Fisher and Ittner, p. 779.

¹⁶ MacDuffie, et al., p. 367.

¹⁷ Fisher and Ittner, p. 785.

¹⁸ Pil and Holweg, p. 398.

limited variety (predominantly body style) they encounter. Further, they did not include in their cost analysis the fixed investments in systems or automation which may help handle variety and complexity.¹⁹

Thus, there appear to be no definitive conclusions concerning the impact of product variety, and thus complexity driven by variety, on manufacturing operations. While combinations and option variability likely contribute to complexity, it is difficult to conclude with certainty whether they contribute significantly or are perhaps second-order effects.

Pil and Holweg point out that “reducing or delaying variety decreases manufacturing and logistics costs, but may also affect design costs and reduce revenue by limiting the offerings in the marketplace.” Other researchers have explored ways to determine the optimum level of variety, but as Pil and Holweg note, MacDuffie, et al. found that they “have reached no definitive conclusions on product variety’s impact on manufacturing operations.”²⁰ While the context of this comment applies to the offering of differentiated product content (attribute variety in products), at a more general level it may apply to the offering of variety across differentiated products in a firm’s product portfolio.

Evaluating Complexity

Raphel deals with the question of complexity management in terms of the decisions made to identify and weigh the costs and benefits of product line expansion. He defines complexity as the proliferation of suppliers, materials, products, processes, and customers that result from customer requirements, revenue and growth targets, competition, outdated or ineffective business policies, and a failure to communicate.²¹

His research work at Hewlett-Packard centered on the development of a model that enabled managers at the firm to more thoroughly populate and evaluate the cost-benefit analysis for the introduction of a new product. He explicitly deals with such things as parts sharing and inventory holding costs resulting from product introductions, and their effects across the supply chain. He further details the hidden costs of individual managers optimizing their product portfolio at the expense of a firm-wide optimization of product strategy. His basic rule of thumb is that complexity should be added to the product line only when its benefits outweigh its costs, a simple application of economic theory on the trade-off between marginal cost and marginal benefit. He notes that detailing some of these costs can be quite difficult.²²

Raphel describes two ways in which firms respond to complexity: trimming their product portfolio, thereby reducing system complexity, and ensuring they are able to cover their costs when introducing any new product that adds complexity to their system. In this vein he develops a recommended approach for decision-making about the introduction of new products, using the concept of a “contribution margin threshold”. Essentially, through his modeling efforts, he is able to determine a relevant minimum threshold that any new product must meet in order to be considered to be a positive business case for the firm.²³

Finally, Raphel notes that the real difficulty in managing complexity is to separate the “good complexity” that customers are willing to pay for from the “bad complexity” that needlessly increases costs and jeopardizes profitability. This will be quite useful in evaluating the question posed as to whether a complexity threshold exists in a plant. Certainly some manufacturing professionals might tell you that

¹⁹ Fisher and Ittner, p. 775.

²⁰ Pil and Holweg, p. 394.

²¹ Raphel.

²² Raphel.

²³ Raphel.

simplicity is the best way to run a manufacturing operation, similar to Henry Ford's famous statement that "they can have any color they want, as long as it is black". However, manufacturing complexity driven by product complexity that yields profits in the marketplace is a critical part of any manufacturer's strategy, especially in a highly competitive arena like the North American motor vehicle market.

These papers lead us to several additional summary points:

1. There is some disagreement on measuring product variety and manufacturing system complexity. Combinations may be misleading; part counts may provide more insight on total system costs; option variability may enable better analysis in the general assembly area.
2. The impact of product variety on manufacturing system performance varies, and in fact may have different impacts across particular aspects of the manufacturing process
3. A manufacturer must evaluate the complexity customers will pay for vs. that which they won't, and make business case decisions for products based on both revenue and cost implications.

Manufacturing complexity, and its associated costs, must be evaluated against the revenues realized by the production and sale of those products driving complexity. In fact, it is not a question of "how much complexity can we accommodate", but rather, how much *must* we accommodate in order to profitably build and sell our products? Though slightly nuanced, the difference in approach is significant. Rather than focusing this research work solely on the question of whether some firm limit to the number of body styles a plant can produce exists, it makes sense to develop a framework for the evaluation of complexity, enabling the consideration of each strategic situation relatively, from the standpoint of potential business results. Estimates of product revenues can then be compared to estimates of production costs (and associated complexity-related costs) to determine the most effective manufacturing strategy, in other words, the one that yields the highest profits.

Flexibility and Complexity

The concept of complexity is tied to notions of manufacturing flexibility. Two authors suggest particularly useful frameworks for considering such flexibility.

Upton characterizes flexibility as "the ability to change or react with little penalty in time, effort, cost, or performance." He proposes to characterize flexibility along three axes: dimensions (what needs to change or be adapted to), time (over what time period), and elements (what is most important – range, mobility, etc.).²⁴

Gerwin defines flexibility as an investment that creates options for a firm. He cites previous research work in suggesting that flexibility be measured through economic value or cost, due to the difficulty of assigning other physical units. He goes on to point out that changes in flexibility must be measured against the trade-offs in cost, productivity, quality, and other objectives. Further, while manufacturing flexibility is viewed by some as an unqualified good, he notes that it is possible for "too much" flexibility to encourage waste, including adapting to uncertainties that should have been eliminated rather than dealt with.²⁵

Gerwin's approach is quite useful in this context, as the view of flexibility as a trade-off is much the same way that we propose to view complexity: a trade-off the firm makes in cost, productivity, quality, and to a

²⁴ Upton, p. 73.

²⁵ Gerwin, p. 397.

lesser extent other objectives, in developing its market and manufacturing strategies. Flexibility may in fact enable the greater accommodation of complexity, essentially buying the firm a real option to adapt to changing market demands.

A Question of Complexity: How many vehicles to build in one plant?

A leading OEM has identified complexity as a critical, potentially limiting factor in its consideration of determining the optimal number of vehicles to produce in a single manufacturing facility, which will in turn influence its enterprise-wide manufacturing strategy. Balancing the number of vehicle entries (number of unique body styles) with the capabilities of its assembly plants, both in terms of volume and product mix capacities, is a critical part of the manufacturing planning process.

Typically the manufacturing planning process proceeds in two manners. First, an overall plan is developed, with the intent of developing a high-level strategy for the number of plants to operate, the product mix and volume capability of each plant, and whether to consider building new plants or closing existing plants in order to meet the requirements of the product plan. The second is driven by marginal analyses: given a desire to design, produce, and sell a new product, where shall it be built? What is the most cost-effective solution considering the total manufacturing system, its capabilities and constraints, and the best known range of information about future requirements?

In evaluating how many vehicles to produce in a single manufacturing facility, many factors are considered, including both aspects of the manufacturing system (floorspace, material flow, conveyance and carrier/locating strategies, etc.) and the product (degree to which the assembly sequence meets standard specifications, adherence to standard assembly locating strategies, etc.). The overall evaluation at a high level considers on one hand the complexity of producing multiple products using shared facilities and equipment, and on the other the cost associated with doing so.

At a fundamental level, the question boils down to one of scale economies and complexity. A manufacturer realizes scale economies by producing a volume of products using the same resources. However at some point, the manufacturer may begin to experience dis-economies related to the complexity of his operations: an increase in costs associated with the production of related products using the same resources. Analyzing the point at which these complexity costs become prohibitive is one way to frame the critical question in this research effort: is there a complexity threshold, and if so, where (how many body styles in a plant)?

With the above introduction to the problem landscape, we establish a multi-part hypothesis:

1. Automotive OEM's manufacturing complexity accommodation strategies are driven by their product portfolio (range, volume, and design), their manufacturing footprint (plants, capacities, and manufacturing flexibility), and their vision of how to approach the marketplace, both today and in the future.
2. A complexity threshold capable of driving management decisions on assembly plant capital investment (decisions of hundreds of millions of dollars) cannot be established through empirical data analysis.

3. Assembly plant complexity can be evaluated from the perspective of the manufacturing strategist or planner as a trade-off, using a capital investment and production allocation optimization model that seeks to minimize total manufacturing cost.
 - a. Specifically, analysis of model constraints directly related to plant complexity (ie, the number of body styles able to be produced in the plant) allows the financial evaluation of various complexity accommodation strategies.
 - b. A portfolio allocation across several different constraint scenarios reveals the incremental value of relaxing these complexity-related constraints. This in turn yields an order-of-magnitude estimate for the amount of complexity-related operating impact/cost that the manufacturer is willing to tolerate in the transition to a less-constrained manufacturing system.
 - c. In particular, a manufacturer can determine the capital investment savings associated with a higher-mix manufacturing strategy, and then evaluate those savings against the anticipated increase in operating costs associated with complexity and plant congestion. This evaluation improves understanding of whether and where a complexity threshold exists both at a macro, manufacturing system level, and a micro, or individual plant level.

This hypothesis shall be explored in more detail in the following sections.

Research Methodology

In order to address this question, it is useful to establish a competitive map of what every major automotive manufacturer produces in each of its assembly plants. This enables two key steps to be taken. First, a benchmark was established to describe the level of product-mix complexity currently being handled across the industry, for each competitor and plant. Second, an evaluation of certain competitor strategies for meeting increased marketplace differentiation demands was performed. This analysis was conducted using all publicly available information.

Beyond understanding what dynamics exist in the industry in terms of both an overall picture and that of individual competitor strategies, it is necessary to evaluate the question of a complexity accommodation limit or complexity threshold specific to the manufacturer in question. This effort takes into account the appropriate and specific details of the products, current manufacturing system design and constraints, and the firm's vision of the future to determine whether a complexity threshold exists for the manufacturer's system, and the plants within that manufacturing system. If the threshold does indeed exist, it must be evaluated in terms of its impact on the overall manufacturing system, and plans made to balance future product volume and mix strategies against the costs associated with the complexity threshold.

In fact, it may be quite difficult to establish a specific threshold based on historical, empirical data analysis. This is true for the following reasons:

- The threshold may be beyond the capability which currently exists in any plant, thus precluding the existence of data to analyze whether and where the threshold exists
- The threshold may not be an "absolute" matter, but rather an element of the relative analysis of alternatives that is considered in making manufacturing investment and product allocation decisions
- The data to examine whether the threshold exists within the realm of currently operational plants may not reveal the specific existence of a complexity threshold. In reality, the data to be analyzed (manufacturing costs, labor productivity, etc.) that would allow a comparison of the impact of complexity in different product-mix scenarios at a plant have a number of factors

affecting them, including the element of increased complexity. Thus, separating out the effects related to complexity vs. those related to product design, labor contracts, or plant management may be quite difficult if not impossible to achieve.

Thus, an alternative and parallel approach was developed in order to help provide insight on the question of the complexity threshold: analytical modeling.

In fact, a modeling approach is often used in situations where data analysis, statistical or otherwise, is perhaps not available, confusing, or more detailed than necessary to develop the understanding necessary to achieve the stated goal. Typically, a model will be developed using the best available data with a number of reasonable and simplifying assumptions intended to enable the accomplishment of the analytical objective with a high degree of confidence. The model can then be subjected to validation testing against real-world scenarios to determine the level of uncertainty associated with the model results. Management users of the model are then armed with not only the results, but the relative confidence with which to use the results in making business decisions.

The model constructed for the purpose of developing insight on and evaluating the existence of a complexity threshold in the manufacturing system and/or particular plants is a linear-program based optimization. It was written in Microsoft Excel with the use of Frontline Systems' Premium Solver Platform engine. The model optimizes the allocation of products to plants by minimizing the total manufacturing cost (capital investment and operating expense) associated with the production of the input vehicle quantities, by platform and body style.

Each of these three methods will be defined in further detail in the following sections:

- Competitive benchmark study
- Empirical data analysis
- Model development

Analysis, Part I: Competitive Benchmark of North American OEM Assembly Plant Complexity

Introduction & Background

The initial analysis step was to benchmark competitors' manufacturing strategies. This was done in order to develop an understanding of their individual approaches to the challenges of scale economies and complexity costs, as well as to determine whether there are trends across the several major automotive OEMs. This analysis was conducted at a macro-level for three primary reasons:

1. Data availability: publicly available information on each OEM's scale economies and complexity accommodation strategies is limited to data on which products and platforms are produced in particular plants, and in what volumes. There is some further information available concerning how these strategies are executed, including the use of sub-assembly and sequencing strategies, labor practices, and particular manufacturing engineering technologies in use by certain OEMs.
2. Manufacturing technologies and processes: the fundamental elements of motor vehicle manufacture do not vary widely by OEM, as each typically configures their plants using technologies that are widely available from industry-wide suppliers. Macro-level processing

techniques are generally well-known and repeated across the industry, but differences exist in the details of the plant configuration, operations, utilization of labor, utilization of automation, etc. Therefore, it is useful to start with a look at how the various OEMs have utilized the similar building blocks of vehicle manufacturing process and technology to meet the requirements for producing their particular array of models and products.

3. Part differences relationship to complexity: as discussed previously, major part differences between vehicles are a reasonable first-cut indicator of the complexity level in an assembly plant, given the requirements these differences drive in capital investment, handling, logistics, labor skill levels, etc. While detail on parts-level engineering is difficult to obtain, these part differences can be viewed at a high level by the major sub-assemblies in which they “roll-up”, in other words, the major pieces that comprise a motor vehicle: platform, body style, chassis, engine, and transmission. Thus, differences between vehicles viewed from these high-level sub-assemblies gives some indication of differences at the lower, component-level, leading in turn to requirements from differences in processing, handling, labor skill, etc.

Each OEM’s North American plants were studied to determine how these plants ranked on a simple “complexity scale” which summed the number of platforms, body styles, chassis, engines, and transmissions being used in the manufacture of these products at each plant. Each plant was then compared on the basis of the products it produces, and how those products do or do not share these major sub-assemblies.

North America was chosen as the focus of the analysis effort for several important reasons: first, data was readily available to support the effort; second, it is one of the most competitive automotive markets, and the basis for many of the OEM’s profits and losses; and third, there are indications that the North American market will continue to fragment in the coming years similar to the trend in Europe discussed earlier. This gives further evidence to the need to understand each OEM’s manufacturing strategy in this market.

The data was gathered from several key industry sources, including Ward’s Automotive Database, The 2005 Harbour Report, The Prudential Securities Automotive Database, and the AutoSitePro Database. Though there are disagreements between these various sources in some specific instances, every effort was made to ensure that the best synthesis was developed from among the sources. These differences between the data sources will not change the overall, qualitative understanding that the competitive benchmark study is intended to develop.

The competitive benchmark charts display the data separated into two primary market segments: passenger car, and Truck-Van-SUV. This latter category includes minivans, full-size vans, and mid- and full-size SUVs. This distinction was made for two primary reasons:

1. All major OEMs, with the exception of Honda, produce pickup trucks that are body-on-frame construction. This assembly method is inherently different enough from the manufacture of body-frame integral vehicles that only one OEM builds both in a single facility: Nissan.
2. Many of the OEMs build SUVs based on either their pickup truck and/or minivan platforms. There are a couple of vehicles known today as small SUVs that are built from car platforms (for instance, Honda’s CRV and Element); these are included in the passenger car tallies, and will increasingly be referred to as “crossover utility vehicles” (those based on car platforms, as

opposed to trucks or vans) as this market segment picks up steam among both customers and manufacturers in the near future.

Two formats were chosen in order to most effectively display the data. Each shows a slightly different view of the same information, painting part of the overall picture of the competitive landscape.

1. Simple Bar Chart: raw data for each plant, summed and grouped by manufacturer
2. Plant View of Product Complexity: Complexity vs. Market Entries at Plant. This chart shows the sum of platforms, chassis, engines, transmissions vs. the number of unique products (body style and nameplate), giving a plant-level view of the complexity associated with building its assigned products. [Note that the number of body styles produced in a plant, while shown on the y-axis of the Simple Bar Chart, is now displayed as part of the x-axis. Thus, the “complexity” scale shown along the y-axis of these two charts is different.]

Consideration was given to whether the data should be scaled, perhaps based on a minimum/maximum scale or an arbitrary 1 to 10 scale. However, it was decided that the choice of scaling factor may obscure the data unnecessarily. Second, consideration was given to normalizing the data based on the number of assembly lines in a plant. A correction factor was introduced as follows:

1. Simple Bar Chart: no normalization made
2. Plant View of Product Complexity: the summed complexity score was divided by the number of “complete” assembly lines in a plant. For instance, a plant with 1 body shop, 1 paint shop, and 1 final trim area has 1 (3/3) “complete” assembly line, where a plant with 2 body shops, 1 paint shop, and 2 trim areas has 1.67 (5/3) “complete” assembly lines.

There do not appear to be any clear trends among the OEMs concerning what level of complexity, as it is measured here, is ideally handled in a single assembly plant (refer to Figures 2 and 3). It is interesting to note that all three Toyota car plants in the study show similar levels of complexity; GM’s plants are widely varied; and Ford and DCX’s plants exhibit, on average, lower levels of complexity than do GM, Honda, or Toyota.

Car Plant Summary

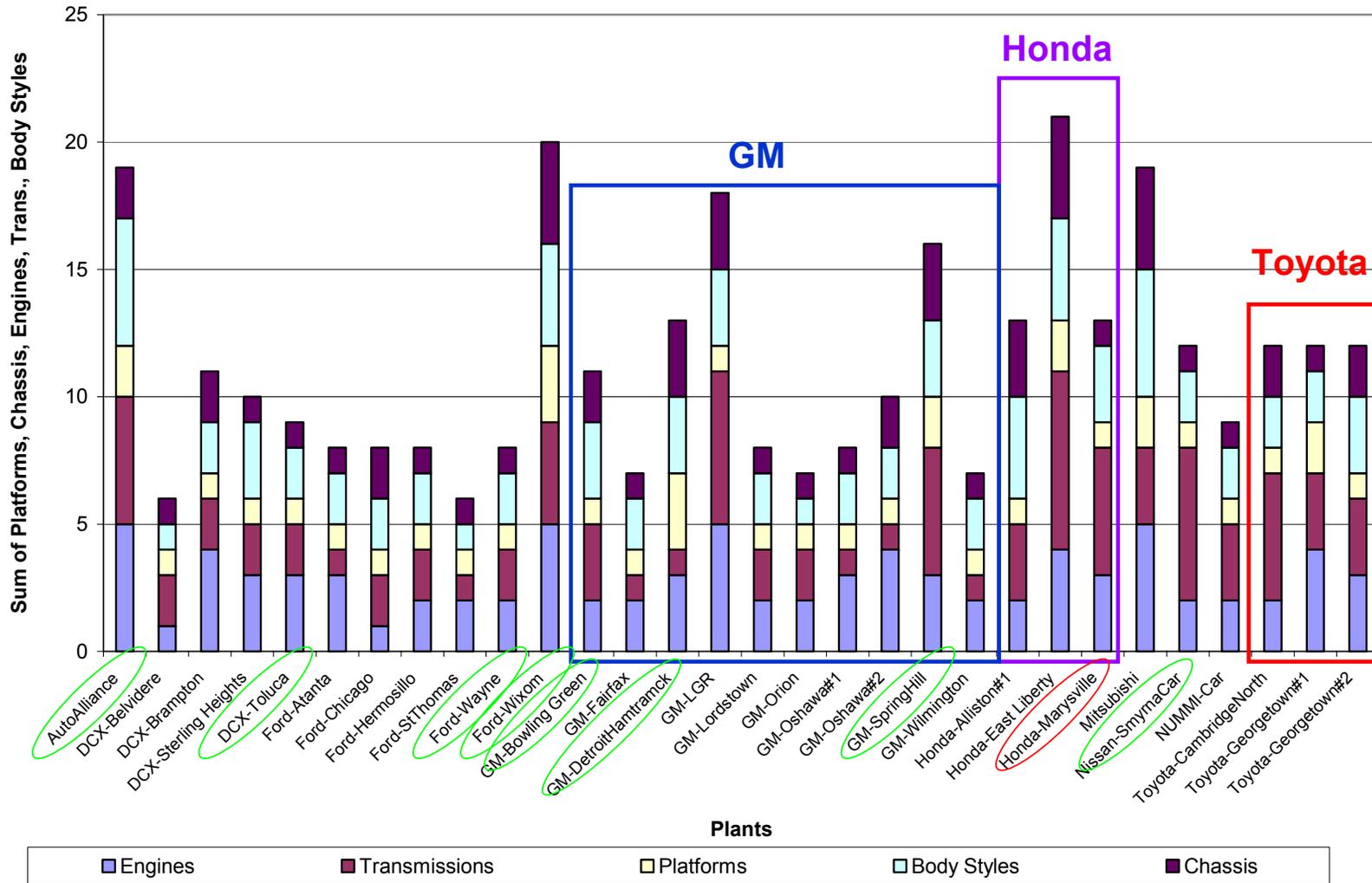


Figure 2: Simple Bar Chart Complexity Scale, NA Passenger Car Plants

Truck-Van-SUV Plant Summary

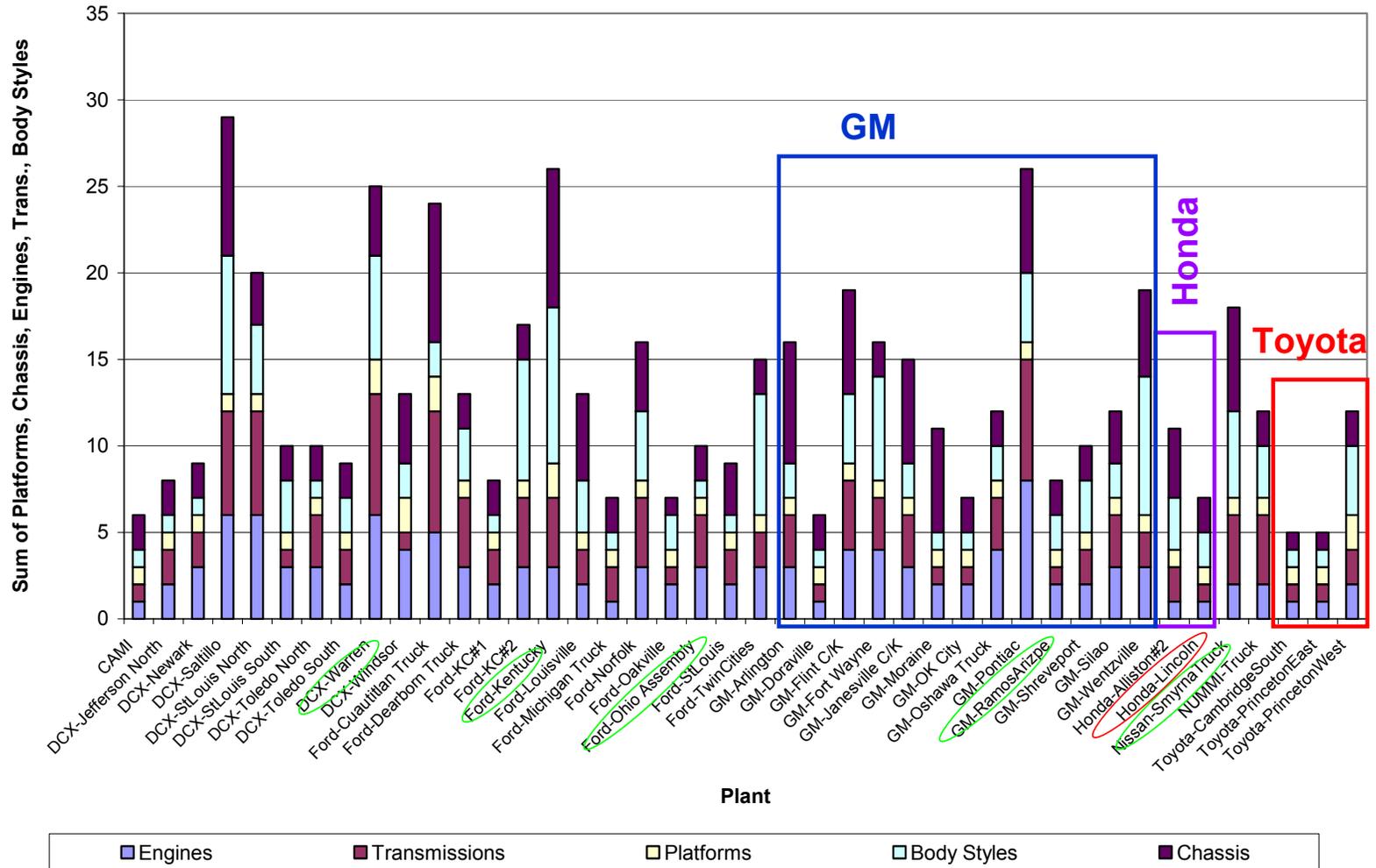


Figure 3: Simple Bar Chart Complexity Scale, NA Truck-Van-SUV Plants

Because the data presented Figures 2 and 3 are not normalized by the number of assembly lines that exist within a given facility (as noted), those facilities with multiple lines have been circled along the x-axis to point them out. While the use of multiple assembly lines (whether in part – ie, 2 body shops with one common paint and general assembly line – or whole – ie, multiple complete lines) within some facilities seems to be more clearly a complexity accommodation strategy, some are clearly not.

For instance, the Ford-Mazda joint venture plant known as Auto Alliance builds the Ford Mustang and Mazda 6 using separate body shops, but then combines these models through common paint and final trim areas. In contrast, Honda’s Marysville plant does have multiple lines, however, each of these lines is capable of building any of the vehicles that Honda produces at the facility – clearly not a complexity accommodation strategy, but perhaps more a strategy to produce vehicles in volume and achieve economies of scale in one plant building.

Figure 4 shows a reasonable grouping of over 2/3 of all North American OEM passenger-car plants in one spot on the chart. This may indicate some level of current consensus about the best operational strategies, but it may also simply reflect the market reality of which manufacturers are able to sell their products in high volumes, while others currently have chosen or are forced to compete with lower volume product entries. Figure 5, which presents the same data for the subset of North American OEM plants in the Truck, Van, and Sport Utility Vehicle (SUV) segment, shows a similar grouping.

There may be an element of historical bias included in this data, as North American plants have typically been able to configure themselves for fewer products at higher volumes given the dynamics of the market in recent history.

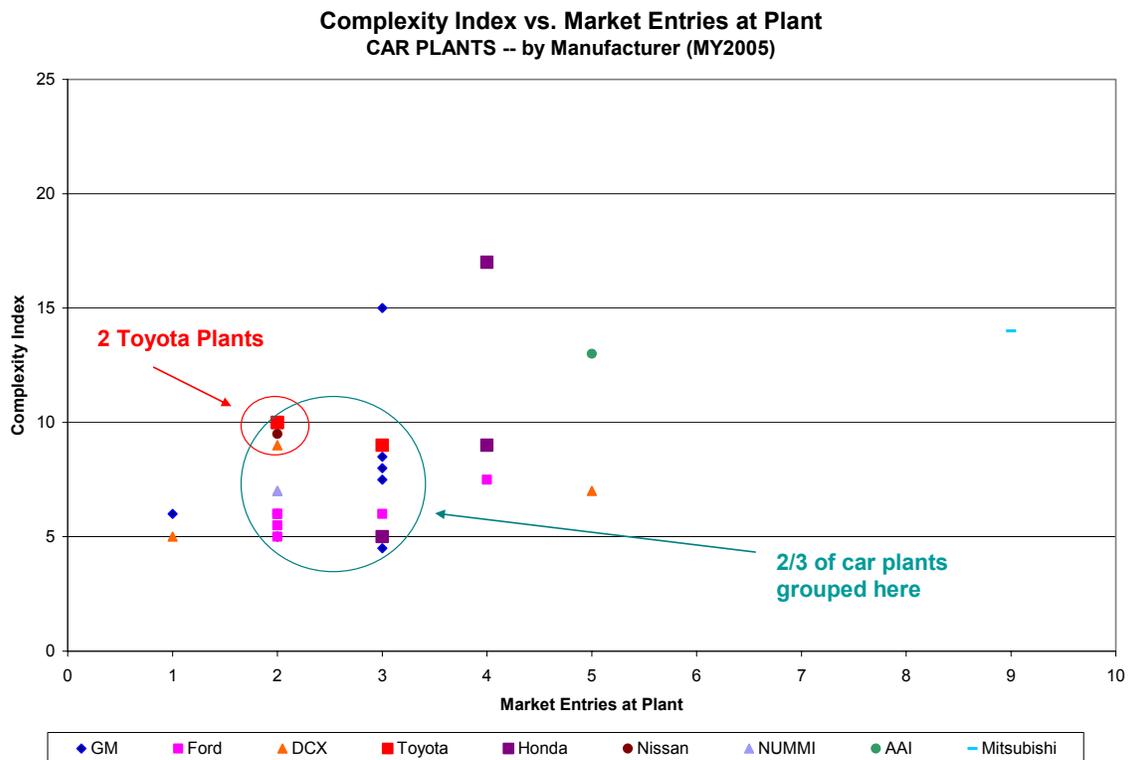


Figure 4: Plant View of Product Complexity, NA Passenger Car Plants

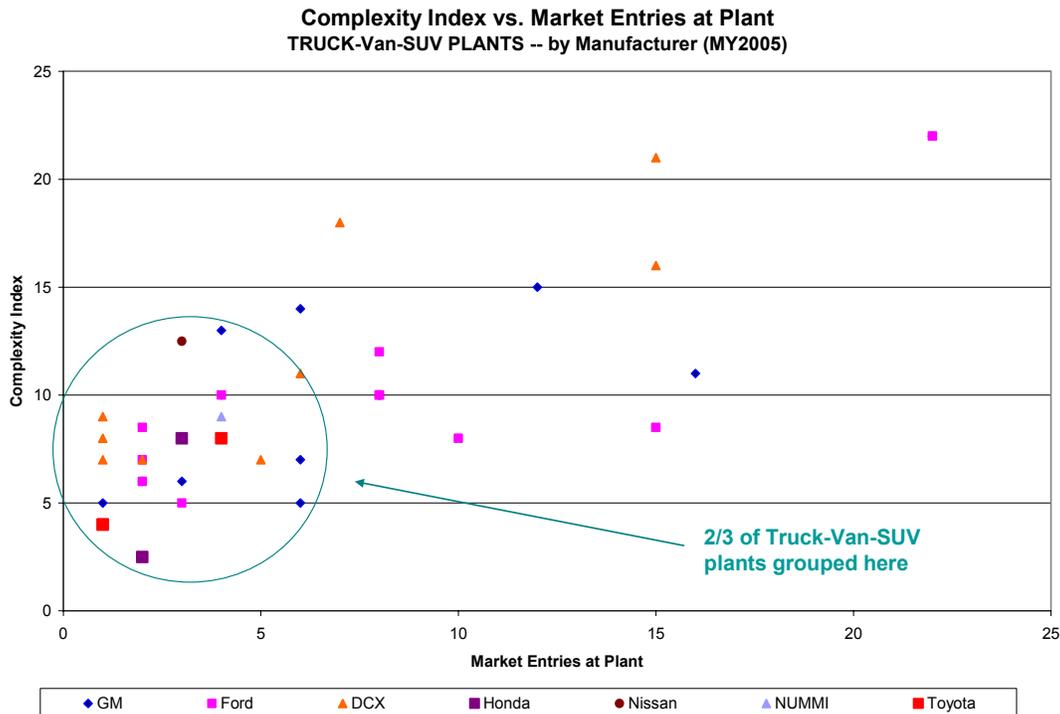


Figure 5: Plant View of Produce Complexity, NA Truck-Van-SUV Plants

Honda's High-Mix Manufacturing Strategy

As noted, one of the challenges facing all vehicle manufacturers in North America is dealing with customers' increasing desire for differentiated products, yet demand for competitive pricing, coupled with the manufacturer's challenge to make the most optimal use of its manufacturing plants. Thus, as product entries increase and average volumes decrease, manufacturers will increasingly look to build more styles of vehicle in a single plant, in order to achieve volumes in line with typical scale economies in the industry (roughly 200k - 250k units annually). The competitive benchmark analysis reveals that one OEM in particular has already embarked on this journey, and is in the process of configuring its plants for high-mix flexible operations: Honda.

Figures 6 and 7 describe visually some of the changes made at Honda's North American assembly plants recently, and changes to be made in the coming months. Its East Liberty plant in Ohio recently produced Accords, and is expected to build the CRV in 2006. Thus this plant is moving from building 4 entries to 6 entries, putting it squarely at the leading edge of high-mix manufacturing among the major NA OEM plants. In addition, its Alliston #1 plant in Ontario is adding capability to produce the Civic Si in 2006, bringing this plant's capabilities to 5 entries. And Honda's Marysville plant in Ohio is expected to begin production of the Acura RDX crossover vehicle in 2006, bringing this plant to 4 entries. Even Honda's SUV and Truck plants are following suit: the Alliston #2 plant began producing the Ridgeline pickup truck for 2005 after moving the Odyssey minivan to the Lincoln plant, and the Lincoln plant is slated to produce a new crossover vehicle in the future.

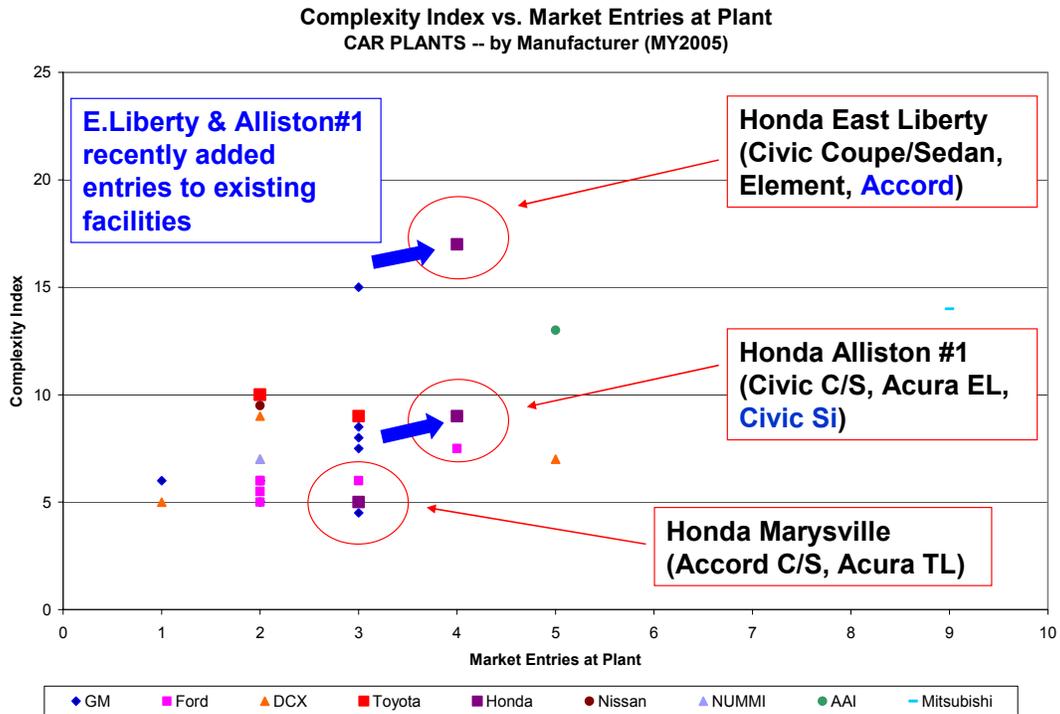


Figure 6: Honda's NA Manufacturing Strategy (Passenger Car) -- Recent Model Changes

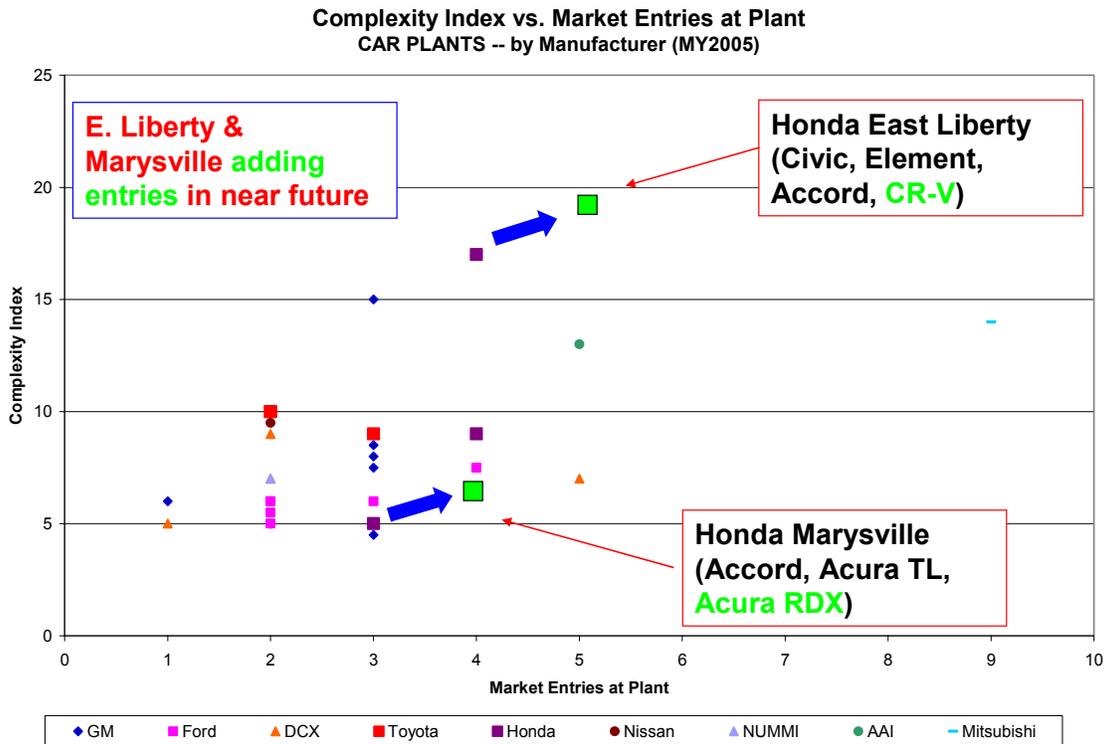


Figure 7: Honda's NA Manufacturing Strategy (Passenger Car) -- Future Model Changes

Honda is pushing the edge of the standard envelope of body-style complexity in its North American assembly plants. The conclusion is that a higher-mix (body styles) manufacturing strategy is not only possible, but being executed by Honda today. Figure 8 (below) makes the contrast quite clear: Honda, more than any other North American manufacturer, produces more body styles per plant than any of its major competitors, and this will become more pronounced in 2006.

If the trend towards increased marketplace fragmentation continues to drive the need for manufacturers to offer more differentiated products, yet do so with smaller volumes, Honda seems to have a competitive advantage in executing a strategy to effectively compete in this changing marketplace. Other OEMs faced with the challenge of more effectively utilizing their existing plant assets in response to increased proliferation and falling average volumes could likely learn from Honda's strategy and approach in their manufacturing system.

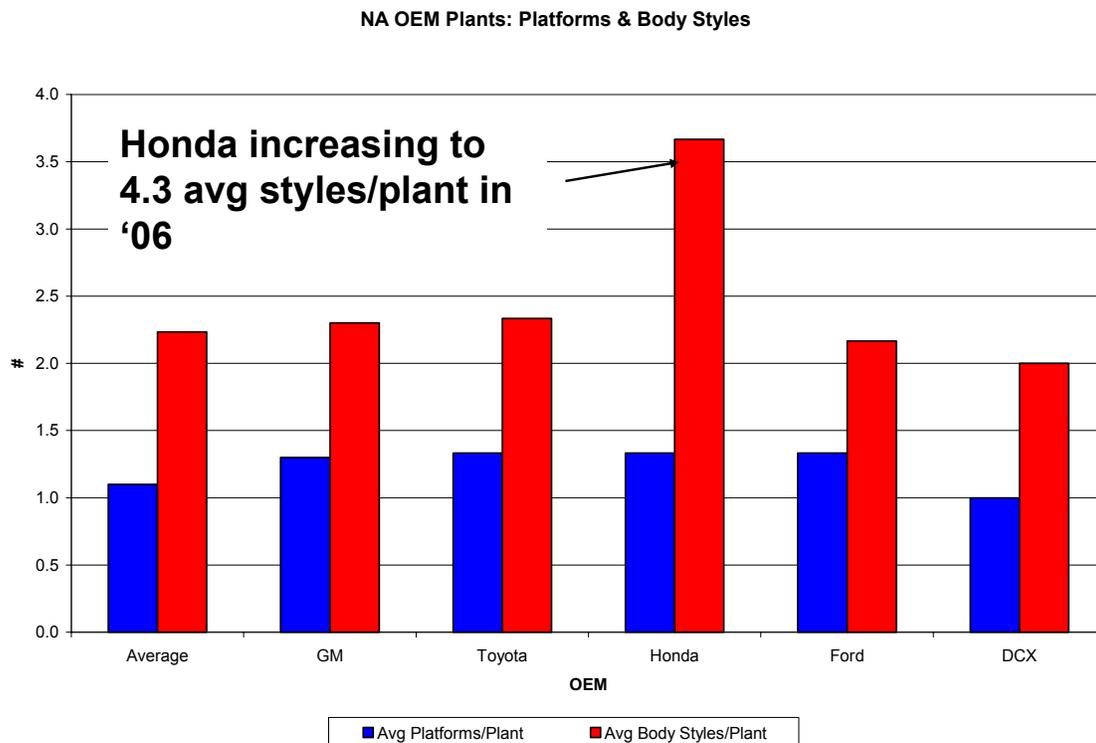


Figure 8: Platforms and Body Styles per Plant, by NA Manufacturer

Detail-level Vehicle Content

The analysis thus far does not consider more detailed levels of vehicle content, and the associated complexity driven by that content. For instance, while we have analyzed at a high level some of the major building blocks of the vehicle (platform, chassis, engine), we have not yet considered differences at the level of such items as sunroofs, stereos, and seats. The question is whether this level of analysis would yield additional information on how the major vehicle manufacturers design their products and operate their plants in light of our bigger challenge to evaluate the existence of a complexity threshold.

As stated earlier, Fisher and Ittner’s research concludes, based on a single plant’s data, that option variability drives higher indirect costs, and typically is accompanied by the addition of excess buffer capacity (direct labor) into assembly stations. MacDuffie, et al.’s research across some seventy assembly plants indicates that increased parts complexity is associated with lower labor productivity, but the effects of option variability are not correlated to lower productivity. Lacking specific data across several manufacturers and plants to compare to either of these results, it seemed appropriate to instead conduct a small case-study of option content in order to make a gross assessment of detail-level content-driven complexity.

Three segments of vehicles were chosen (small, mid-size, and mid-size Luxury), and vehicles from GM, Toyota, and Honda were selected within these categories. Then, from over 125 different types of vehicle content (listed in the AutoSitePro database), 94 were selected as appropriate for these classes of passenger car. (For instance, items specific to pickup trucks and minivans were eliminated, including sliding side doors and sliding rear windows).

The number of line items of content offered on each vehicle was counted, and then classified as either a “trim-level” or “free-flow” option. Trim-level options are those items of vehicle content that come as part of a trim or option package (i.e., part of the manufacturer’s bundling of options in its LX or EX trim levels), and are not available as stand-alone options. For example, if power windows are a “trim-level” option, they are only available on a vehicle of a particular trim level, and cannot be ordered for the vehicle regardless of trim level. Free-flow options are available to be put on any vehicle, no matter the trim level ordered (by the customer or dealer, depending on the circumstance). This resulting data is shown in Figures 9-11.

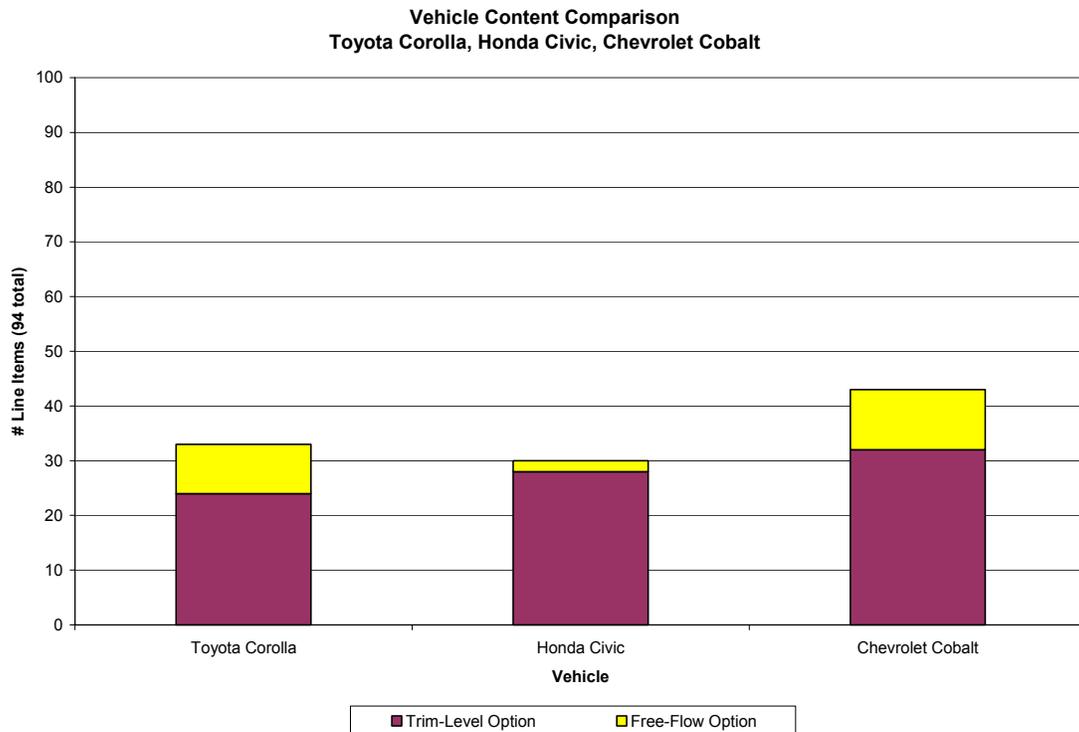


Figure 9: Vehicle Content Comparison -- Small Car Segment

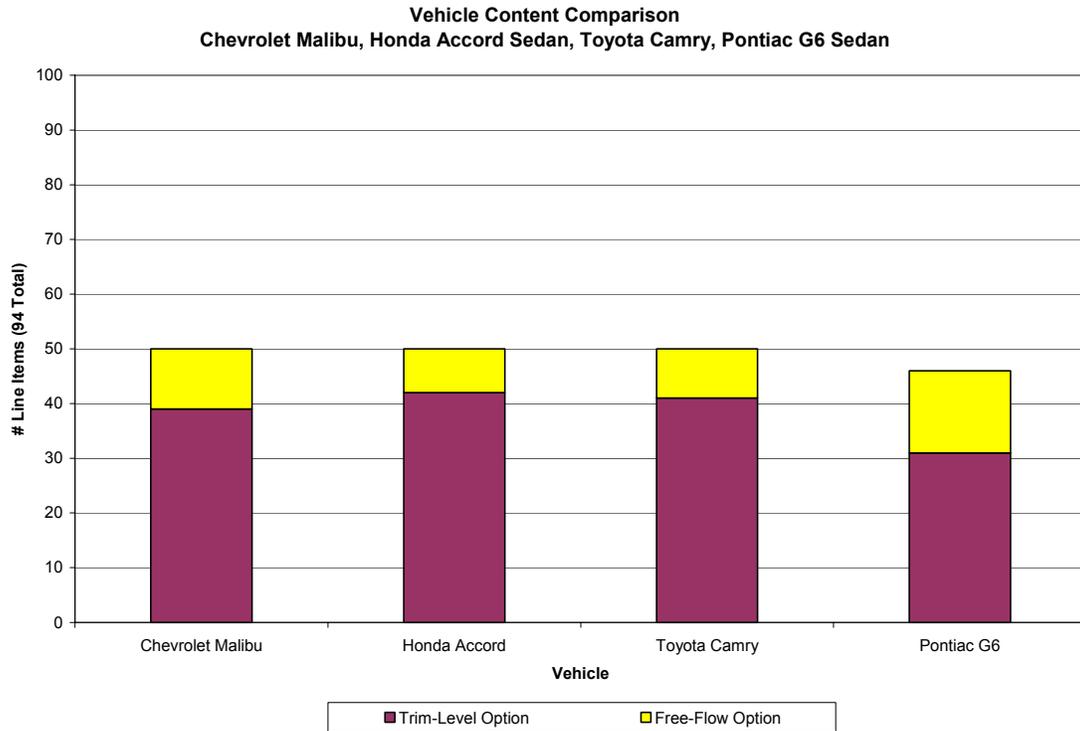


Figure 10: Vehicle Content Comparison -- Mid-Size Car Segment

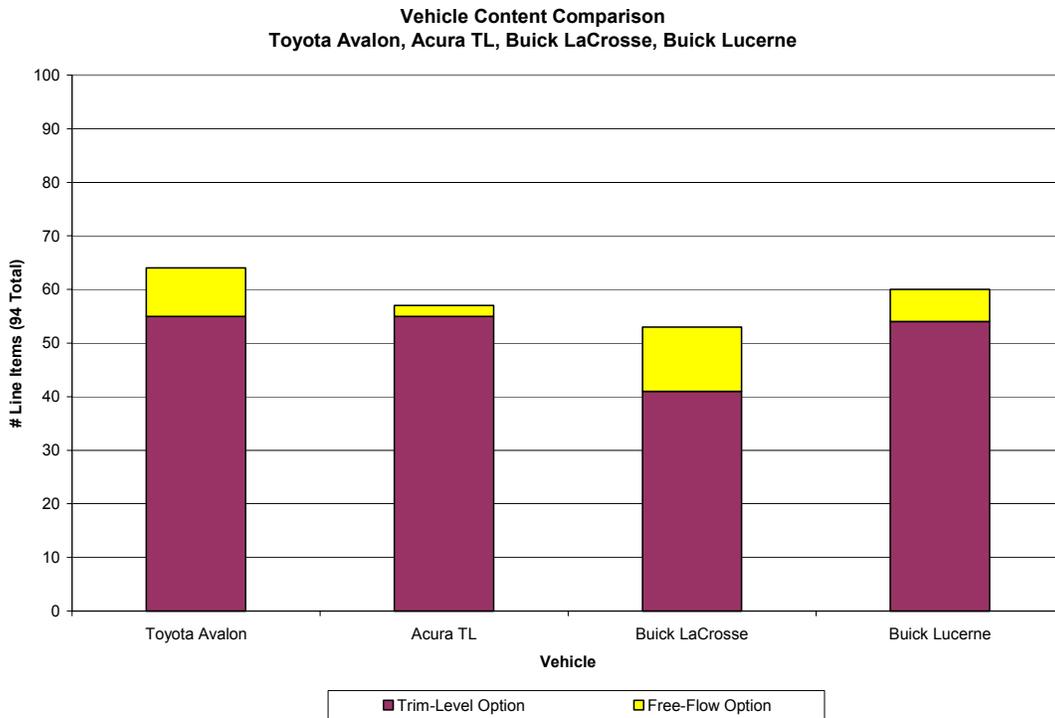


Figure 11: Vehicle Content Comparison -- Luxury Car

It is striking yet reasonable that these different vehicles offer very similar levels of content: in order for the manufacturers to compete for customers in the same market segments, they must provide similar features and content in their vehicles. There is some difference in how the manufacturers choose to provide this content: Honda makes extensive use of trim-level content, where GM and Toyota utilize some level of free-flow options. Going one step further, free-flow option content was analyzed for these same vehicles and segments, and categorized according to its installation location: dealer or port-installed (DIO/PIO), and plant-installed. The results are displayed in figures 12-14.

Option Content Analysis: Where Installed

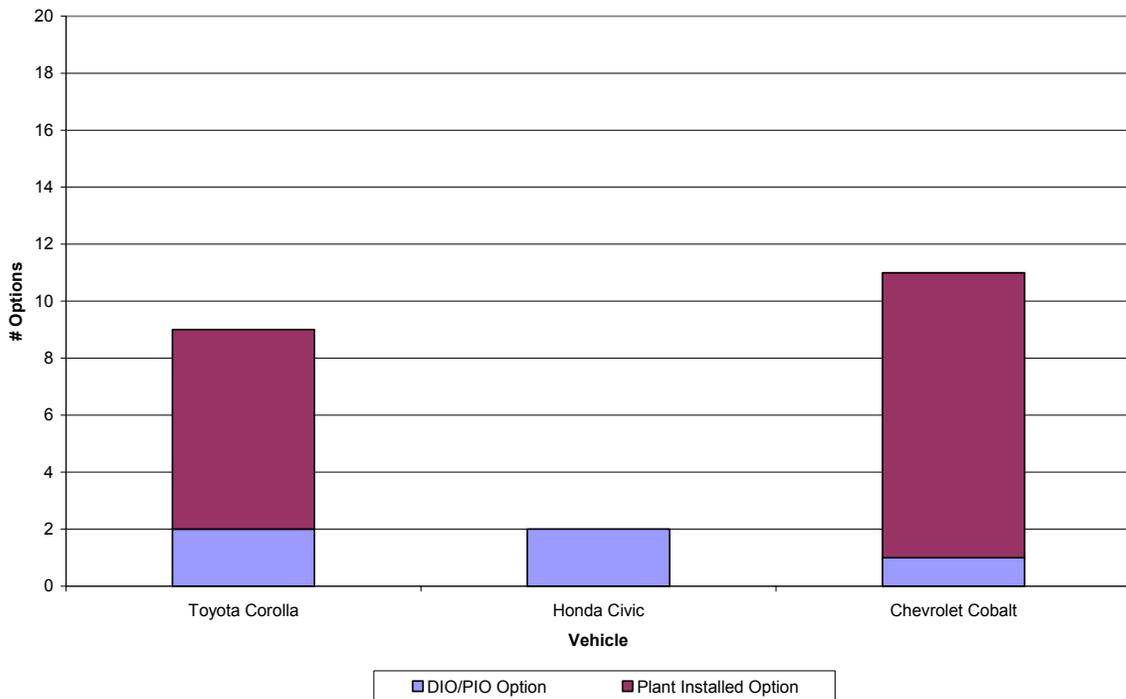


Figure 12: Option Content Analysis -- Small Car Segment

Option Content Analysis: Where Installed

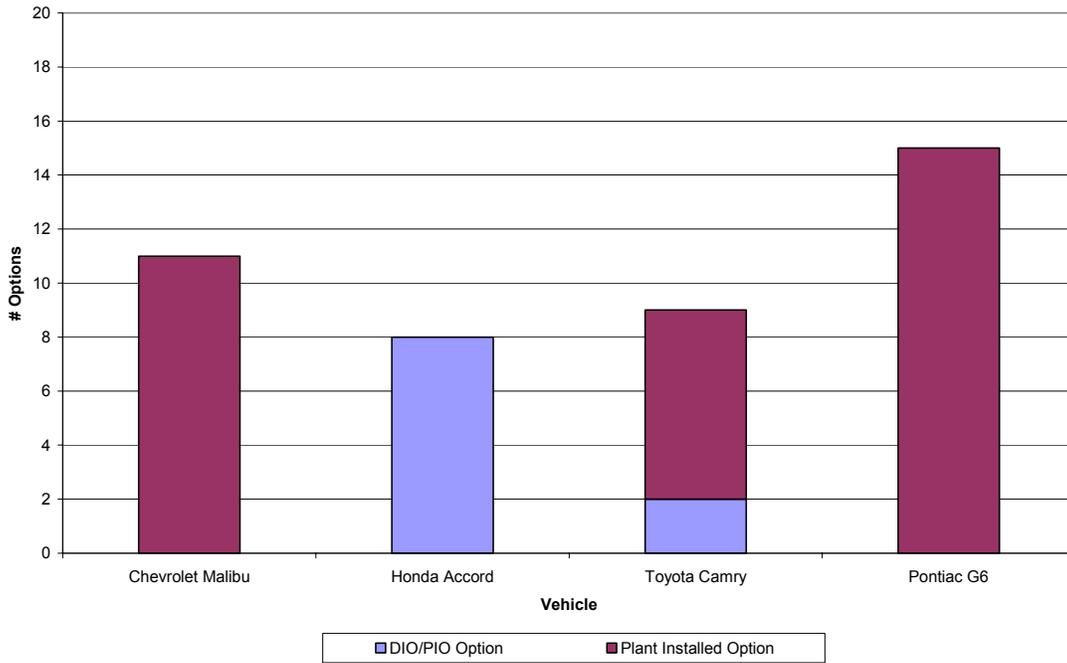


Figure 13: Option Content Analysis -- Mid-Size Car Segment

Option Content Analysis: Where Installed

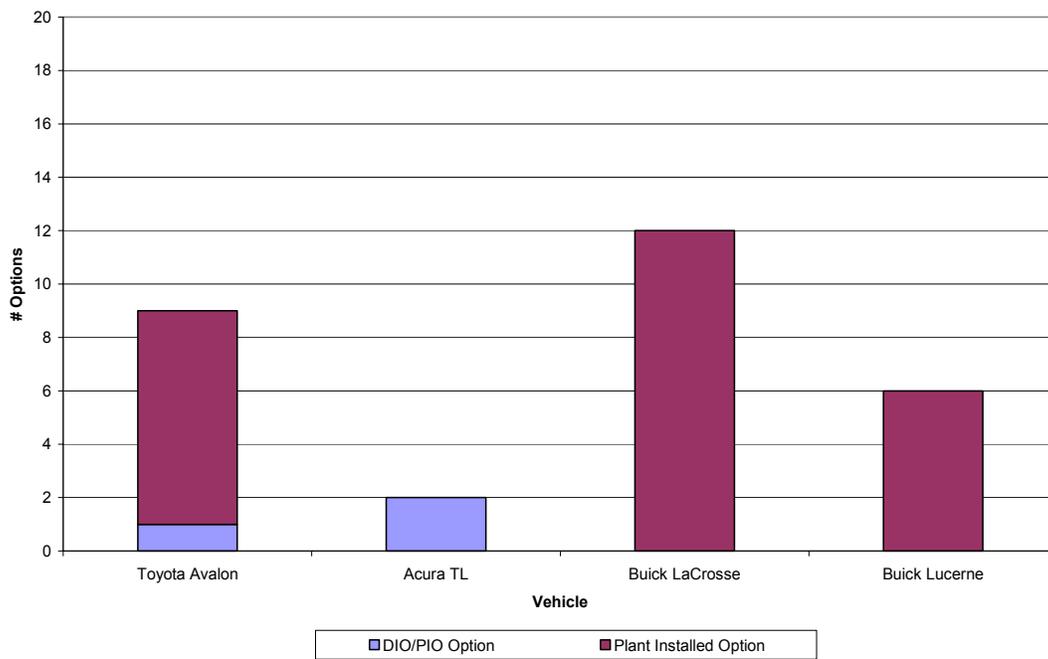


Figure 14: Option Content Analysis -- Luxury Car Segment

It is interesting to note that while Honda makes nearly exclusive use of dealer-installed options for any content that it provides as free-flow; GM and Toyota make limited use of such strategies. Without further insight on Honda's strategy, it is not possible to definitively categorize their choice as a complexity-reduction strategy; it may in fact be a late-point differentiation strategy to satisfy customer needs as close to the point of sale as possible, that happens to have the added benefit (and costs) of removing these items from the assembly plant. It may also be the case that Honda's retail dealers clear significant margins on these option sales, and thus part of Honda's overall strategy is to help their dealers make this money.

The overall conclusion is that each OEM provides similar levels of content for vehicles competing in similar market segments, and as such, these vehicles will have ***similar levels of content-driven complexity for the plant to accommodate***. If manufacturers build vehicles of similar classes in their plants (typically the case), there will be limited differences in content-driven complexity between these plants. On the other hand, if manufacturers choose to build vehicles of widely dissimilar segments in a single plant (ie, luxury and entry-level), there would be some level of differentiation possible between the OEMs' plants.

It should also be noted that Honda's strategy appears to be consistent with the findings of Fisher and Ittner. As noted previously, Honda's manufacturing plants are currently handling a greater level of body-style complexity than its competitors. And Honda has chosen to bundle or delay installation of the options if offers consumers more so than its competitors, while still providing fundamentally the same level of content. Thus if Fisher and Ittner's results are more widely applicable, Honda may be realizing a reduction in indirect costs associated with the production of multiple vehicle types (and the option complexity that includes), as well as a reduction in the direct-labor buffering necessary to produce this level of variety. This may be an enabler of their strategy to produce at seemingly high body-style complexity levels inside a single assembly plant.

Inside the Plant: Operational and Strategic Differences

Finally, it is important to point out that the data analysis presented thus far looks only at the major building blocks of the vehicles, and the different types of vehicles produced at each plant. There are certainly differences in the manufacturing system setup that each OEM employs; without detailed, inside knowledge of each plant's strategies and operations, an analysis of these differences cannot be performed. However, some insight on the particular OEM's strategies can be gained from publicly available data.

In order to develop a better understanding of whether OEMs are achieving their relative complexity levels through the use of outsourced sub-assemblies, data from the 2005 Harbour Report was analyzed. Figure 15 details the number of sub-assemblies produced inside the plant vs. brought in from an outside supplier, regardless of whether that supplier is simply another plant within the OEM's network, or another company.

**Major Sub-Assemblies Operations performed Inside Plant
as defined by Harbour Report 2005**

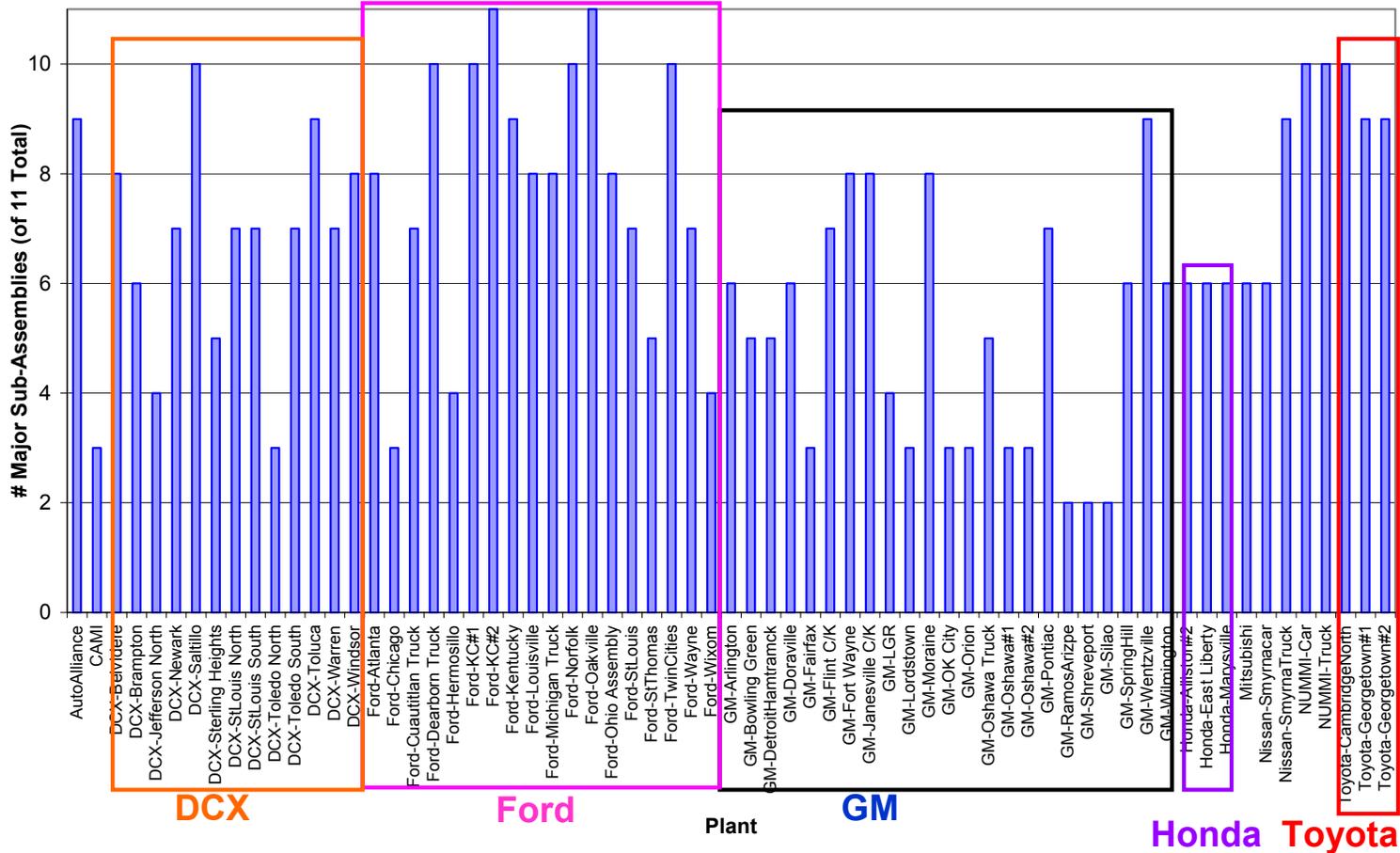


Figure 15: Sub-Assembly Operations Performed Inside OEM Plants²⁶

²⁶ 2005 Harbour Report.

The conclusions reached here are that Toyota, of all the North American OEMs, produces nearly all of the listed major sub-assemblies inside its assembly plants; Honda produces about half, and GM tends to outsource more of these sub-assemblies than it produces in-house. Again, without detailed knowledge of the decisions made to out-source or in-source, strong conclusions about this data are difficult to make, as some plants may have employed particular strategies for reasons other than handling complexity. However, the data does provide another piece of the puzzle to understand the overall manufacturing strategy of the major OEMs.

A Transitioning Marketplace: Increased Product Proliferation, Falling Average Volumes, and Lessons from the European Passenger Car Market

As mentioned earlier, a recent study (Pil & Holweg, 2004) analyzed the progression of the European passenger car market from 1990-2002 in terms of manufacturer’s strategies for balancing fundamental product commonality required for competitive pricing with the differentiation necessary to attract customers with varying product needs. They studied the number of vehicle platforms and body styles being built in Europe over this time period, along with the associated production volumes of these vehicles. The data suggest that the motivation for this research effort, namely the increasing number of differentiated products in the marketplace coupled with lower average product volumes, has in fact played out in Europe to some degree over the last decade. Manufacturers have responded by building more vehicle entries (products) based off the same fundamental engineering, structure, and components. This is clearly seen in Figure 1 and Table 1 (shown earlier).

However, most interesting for this work is the relative position of the North American market in regards to this trend. Using publicly-available data from both Ward’s Automotive Database and from the data compiled for the (previously presented) competitive benchmarking, there is remarkable agreement even when comparing across passenger car and truck/SUV platforms. Table 2 compares the European passenger car data (2002 snapshot) to that compiled from North America (2005 model year). The result is striking: while European-producing manufacturers have transitioned to offer significantly more differentiated products (unique body styles) and consolidated these products’ fundamental underpinnings over the past decade, the North American market has yet to follow suit. North American producers average ~2 body styles per platform, compared to a European average of nearly 4; the European producers are building more vehicles, on average, from the same platforms, and are therefore able to tolerate the lower average volumes per differentiated body style.

Table 2: Comparison of North American and European Automotive Market Characteristics

	NA 2005 Ward's Automotive Online Database (all vehicles)	NA MY2005 Competitive Benchmark Data (cars only)	Europe 2002 Holweg & Pil Study (cars only)
# platforms	83	33	46
# body styles	191	67	179
# body styles per platform	2.3	2.0	3.9
Average volume per platform (000s)	189	166	269
Average volume per body style (000s)	82	85	69

If the trend illustrated in Figure 1 concerning changes in the European passenger car market is indicative of what has begun in the North American marketplace, divisions of many of these same manufacturers will need to consider how they may effectively double the number of products derived from each platform and deal with the lower volumes per entry that will be associated with these changes. Honda appears to have a head start in this area through the design and implementation of its flexible body system that reportedly can accommodate up to eight unique body styles on the same manufacturing line. Each manufacturer must give careful consideration to the changes necessary in their manufacturing systems in order to make this transition. This consideration, in fact, motivates Part II of this study.

Analysis, Part II: Developing Insight on the Existence of a Complexity Threshold in High-Mix Automotive Assembly Plants

Introduction

Increasing product differentiation and proliferation in the marketplace, coupled with relatively slow overall growth rates in the sales of motor vehicles in North America, is decreasing average volumes per vehicle entry over time. It is expected that this trend will only accelerate, as more manufacturers carve out market niches in an attempt to profitably serve customers with differentiated products. This presents a significant challenge to manufacturers who must transition their manufacturing systems to respond to this new reality of customer demand.

Fundamentally, if existing scale economies remain at or near present levels, manufacturers will be faced with the challenge of producing more unique products in a single assembly plant, in order to achieve the necessary volumes to run at or near full capacity utilization. This will theoretically ensure that the cost per vehicle is as low as possible in a highly competitive market.

A typical vehicle assembly plant today in North America produces two or three unique body styles, typically based on the same underlying platform, achieving annual volumes of between 200,000 and 250,000 units per year. Yet if this same plant sees average product volumes cut in half but must still achieve similar scale economies, the manufacturing system must adapt to be able to produce four, five, and perhaps six vehicles or more in order to maintain cost-effective vehicle production.

One approach is to pursue a strategy of lowering overall product volumes required to achieve the same economies of scale. There are at least two ways in which this can be achieved. First, vehicle assembly plants can be located in regions of the world where labor costs are much lower than that of a current facility. This enables high-cost capital expenses (automated equipment and tooling) to be traded for lower-cost labor solutions in manufacturing, lowering the total capital cost required for the facility, and thus lowering the number of units necessary to achieve reasonable market-rates of capital cost allocation on a per-unit basis. The manufacturing facility is then able to produce in smaller volumes while still achieving scale economies.

There are, of course, good reasons to keep manufacturing facilities in high-labor rate areas, including supply-chain strategies that demand customer responsiveness, and cost savings associated with the transportation of heavy, bulky items. When a manufacturing activity will remain in a high labor cost area, economies of scale may be lowered somewhat by investing in flexible equipment and tooling. Flexible machinery is adaptable to successive product generations, and the associated capital costs can be spread

over fewer units on an annual basis. These efforts will take time to develop and implement, and in the meantime, the OEM must adapt its existing systems and facilities to market realities.

Challenges of Higher-Complexity Assembly

There are a number of challenges associated with the transition towards higher-body-style-mix assembly plants. First, there are some developments in processing and manufacturing engineering technology that could help in some plants. For instance, framing devices in the body shop today typically handle three or four different types of body sides; the plant must have capability for more. This can be achieved by installing parallel processing systems, but at the expense of adding capital equipment, handling new process-flow challenges, and using precious floor space.

Additionally, a typical strategy is to manufacture the many unique pieces of a differentiated vehicle in their own dedicated sub-assembly areas, then bring them to a common main line for processing and assembly steps that are similar across vehicles. This enables the manufacturer to achieve economies of scale on the main line, while simplifying some other tooling and equipment that processes the sub-assemblies. However, with increasing numbers of unique sub-assemblies going into differentiated products, there will be greater challenges fitting all of the sub-assemblies cells into the plant, synchronizing their operations, and providing for the appropriate buffers to ensure smooth operations.

Creative solutions can be used to adapt existing equipment to handle more unique types of vehicle styles through the use of programmable and reconfigurable tooling, and these efforts are bearing fruit in assembly plants today. Ultimately, a combination of creative adaptations of existing equipment along with the development of new processing technology and equipment should enable the transition to higher-mix strategies over time.

Increased product mix will lead to challenges associated with material handling and flow throughout the assembly plant. For instance, many pieces are delivered via fork-truck in dedicated containers from a central material storage area to the line-side area where they are to be utilized. An increased number of unique parts to deliver may mean increased fork-truck traffic, a need for additional line-side space to accommodate the additional containers, and a need for additional central material storage resulting from a decreased sharing and pooling of inventory possible when producing differentiated products.

Increased product mix presents special challenges at the point of assembly. The assembly line worker must now make additional decisions about which parts to put on which vehicle, either by reading a manifest taped to the vehicle or perhaps with the help of an error-proofing system tied to a real-time vehicle sequencing information system. This may require additional or special training, and introduces greater opportunity for mistakes and quality problems. In addition, these effects may tend to reduce labor productivity, adding to cost pressures.

Certainly some of these challenges can be addressed through the use of such methods as error-proofing systems²⁷, the sequencing of parts to the assembly line (synchronized with the vehicles being built)²⁸, and the kitting of parts to assist the assembly worker rather than requiring on-line parts selection from a line-side rack²⁹. However, each of these potential solutions costs money, and adds to the overhead expenses

²⁷ Dennis, p. 91.

²⁸ MacDuffie, et al., 1996, p. 354.

²⁹ Fisher and Ittner, p. 775.

of the plant, whether seen in increased labor to kit parts or increased capital expense to install the systems and equipment for error-proofing or sequencing.

Thus, the introduction of additional differentiated products to the assembly plant presents numerous challenges. Successfully addressing each of these will require a delicate balance of capital, direct labor, and indirect operating expenses. Each of these expenses must be balanced against the cost-savings realized as the plant achieves scale economies from producing multiple products utilizing the same plant and much of the same equipment. The additional products allow the plant to remain closer to its most cost-effective operating band near full utilization, achieving scale economies but with higher complexity costs.

Addressing the Idea of a Complexity Threshold

As previously stated, the fundamental question motivating this work is whether and where dis-economies due to complexity emerge at some point (ie, building some number of differentiated products). Clearly the answer to this question has far-reaching impacts for the manufacturer's strategy about how to most cost-effectively produce vehicles across its assembly plants, how to transition the firms' manufacturing footprint over time to adapt to future production requirements, and how to shape its product portfolio (and thus anticipated revenue prospects) with respect to its manufacturing capabilities and costs.

But the existence of a complexity threshold is really a relative matter: an absolute "answer" that producing more than four vehicle styles in a plant is prohibitively expensive (ie, "the threshold is four") is not fully satisfactory. Producing more than four vehicle styles in a plant *may* indeed be costly due to the complexity of this operation, but that cost *may* be more than offset by the revenue gains from the additional product to be produced. Moreover, a particular plant may be the least costly alternative to produce a product.

The firm must balance the expected revenues from its product portfolio with the anticipated costs of design and manufacture; in the marginal case, the firm should evaluate the revenues expected from the next vehicle to be added to the portfolio against the costs associated with its production. There may be a case where the costs of producing a 5th style in a plant is still outweighed by the revenue gains of the product, such that an absolute "4-style limit" for any plant would be superseded in such a "special case."

Thus, the firm really must consider complexity in terms of its costs **and** potential benefits. The notion of a complexity threshold is a relative term, subject to the potential trade-offs that must be made in fully evaluating either a particular manufacturing allocation, or evaluating the higher level manufacturing strategy that should be pursued over time.

Two methods were used to tackle this question. First, an empirical analysis was performed on one manufacturer's available data to determine whether the question could be answered through the study of operating data. Second, a parallel effort was undertaken to effectively model the manufacturing system at a macro financial level, in order to value the ability of a plant to accommodate a particular level of complexity as seen through the number of body styles (unique products) the plant produces. This approach helps to determine what value the manufacturer would realize from a higher-mix vs. lower-mix strategy, and thus what complexity cost the firm would be willing to tolerate in shifting to build a greater number of products in a single plant.

Part A: Analysis of a Manufacturer's Operating Data

Development and analysis of appropriate historical data to determine both the capital and operating costs associated with increased product mix in a vehicle assembly plant would ideally enable the manufacturer to make decisions about its manufacturing strategy. In particular, an ability to see whether operating costs began to increase disproportionately after the addition of the n^{th} vehicle to the plant, or the ability to determine whether the capital investment necessary to enable the manufacture of the n^{th} vehicle was not cost-effective would be highly desirable. Ultimately, the combination of both operating and capital impacts into a business case analysis (coupled with projected revenues) is required to make a good management decision about whether to produce the n^{th} differentiated product in a particular plant, or to produce it somewhere else.

Manufacturing finance and operations data were obtained and analyzed for the periods before and after the introduction of additional new, differentiated products to several of the manufacturer's plants. This seemed to be the most reasonable way to analyze changes in cost that were influenced by the addition of a new product to a particular plant. Because the manufacturing finance and operations data are proprietary, they cannot be displayed or discussed in detail. However, the following is a general explanation of the data analysis.

Manufacturing costs were analyzed on a gross and per-vehicle level, including the various line items of detail that roll-up to the total manufacturing cost figures. This includes direct labor, indirect labor, indirect material, etc. Direct materials costs (ie, vehicle parts) were not analyzed as data were unavailable, and additionally, unlikely to yield results.

The cost per vehicle figures were analyzed raw as well as normalized to a full-production rate (ie, any overtime costs to produce additional vehicles removed, and any savings resulting from producing fewer vehicles than capacity added back in); depreciation expense was also removed from the figures (so as to eliminate any differences in depreciation treatment between plants).

The manufacturing cost per vehicle data does not appear to show any meaningful relationship to the addition of new vehicles to the assembly plant. It is important to note that manufacturing operations data incorporates many factors, just one of which is the complexity of the operation being performed in the particular plant. For instance, while data normalization for volume changes is quite practical to do, there are a number of other factors inherently more difficult to separate out of the data, including the effects of labor contracts (that may or may not enable the organization to adapt flexibly to the production of the additional product), the addition of capital equipment and systems that simplify (or perhaps make more challenging) the assembly process, and the particulars of the manufacturing plant itself (each is a unique entity) that may influence or affect the plant's ability to build a differentiated product.

Additionally, operations data on several plants' "conversion rates" were obtained and charted across these same points of vehicle introductions in a plant. The conversion rate is a measure of the amount of direct labor necessary to build the vehicle, given the amount of labor content the vehicle theoretically requires for assembly. In other words:

$$\text{labor content} * \text{direct labor conversion rate} = \text{direct labor hours per vehicle}$$

The conversion rate analysis shows that there is very little, if any, change in the amount of direct labor applied at the plant to build vehicles across the time period when a new product was added. This seems to indicate that the manufacturing system has accommodated these new products without affecting the

plant's direct labor costs. This may be a reasonable conclusion, given that direct labor is in many ways a fixed cost when considering the long-term union contracts in place, and thus a manufacturer would be expected to take a number of steps to mitigate any effects that adding a product to a plant would have on its requirements to add direct labor. Specifically, the manufacturer is likely to substitute capital investment or other operational spending for direct labor in order to avoid obligating the firm to long-term changes in plant employment.

Analysis of kitting and sequencing costs broken out separately from the per vehicle cost data as well reveal very little. There do not appear to be any reasonable conclusions to be drawn about the impact of additional vehicles on kitting and sequencing costs, at least in the range of vehicle additions (# of vehicles per plant) that we are able to study with this historical data.

It is fairly clear that an analysis of such data across more plants and vehicle programs is unlikely to produce the analytical result desired, namely, to determine whether and where dis-economies due to complexity begin to affect a plant implementing a higher-mix manufacturing strategy. As noted earlier, this may be a result of the lack of clarity in the data, a lack of data collected in a manner consistent with this analysis, and/or the fact that the threshold for dis-economies may well exist beyond the scope of current data and plant installations. Still, it is useful for the manufacturer to know that this question is not likely answered definitively with this approach using currently available data.

Part B: Modeling

As the empirical data analysis does not seem to enable a complexity threshold evaluation that will robustly inform the multi-hundred million dollar decisions made for plant capital investments, the most reasonable alternate method is to use a model to estimate the complexity trade-offs inherent in product allocation decisions.

The model's purpose is to assist in the manufacturing strategy decision-making process, which is described in the following section. In doing so, the strategist/planner is able to determine what value the manufacturer would realize in applying various complexity limitations or constraints at one or more plants when evaluating a product allocation decision. This value is estimated in terms of both the manufacturing investment and per-vehicle production costs. The model thereby informs the manufacturing strategy decision concerning the level of plant complexity to be executed.

The Allocation Decision Process:

1. Identify vehicles to be produced (both new and existing): the product portfolio
2. Develop vehicle demand forecasts
3. Determine the optimal production plan for product portfolio forecast
4. Make capital investment decisions that enable production of desired vehicles
5. Execute the capital investment strategy
6. Execute the manufacturing allocation strategy

(The ability to determine an optimal production plan and capital deployment decision under uncertain demand will be addressed in a following section, but is beyond the scope of this work).

The model optimizes the allocation of each of the manufacturer's products to its plants by minimizing the total manufacturing cost (capital investment and operating expense) associated with the production of the required vehicle quantities. [While referred to as an "allocation", the optimization done at this point is

not truly a manufacturing production allocation. Rather, it is a pre-production allocation for the purpose of establishing the best plan for capital investment deployment, given the required production forecast and capital investment decisions made previously.] By implementing constraints associated with complexity at the plant level, the model drives the evaluation of manufacturing investment alternatives.

The optimization model, as fully implemented for this research work, includes all of the manufacturing plants across the globe that the manufacturer operates, as well as all of the product models (body styles) that the manufacturer sells across globe. Specifically, the model utilizes 22,112 decision variables, 27,984 constraints, 9452 bounds, and 12,600 integer variables. Due to the extremely large nature of this implementation in Excel, an upgrade to Microsoft's standard solver plug-in was obtained (Premium Solver Platform from Frontline Systems, Inc). The following sections introduce the model's notation, describe the model's mathematical formulation, summarize the objective function and constraints, and finally, discuss several of the "real world" issues associated with the formulation.

Model Notation

Model Variables and Constants :

i : plants

k : body styles

j : platforms (a product - family platform includes a number of body styles)

r : countries with assembly plants

s : countries with vehicle demand (planned sales)

I_r : Set of assembly plants located in country r

$B_{i,j}$: Plant - Platform Manufacturing Investment Estimate for plant i and platform j

(i.e., cost to add platform j capability to plant i ; zero value indicates capability currently exists)

D_s : Demand in country s

D_k : Demand for body style k

$D_{s,k}$: Demand from country s in body style k

$E_{i,k}$: Plant - Body Style Manufacturing Investment Estimate for plant i and body style k

(i.e., cost to add body style k capability to plant i ; zero value indicates capability currently exists)

G_i : maximum number of platforms that can be produced at plant i (user - constraint)

H_i : maximum number of body styles that can be produced at plant i (user - constraint)

J_i : plant i 's straight time capacity (annual volume)

K_i : plant i 's overtime capacity (annual volume)

κ : Overtime Factor (estimate of premium over standard cost per vehicle)

V_i : Annual volume of vehicles produced at plant $i = \sum_k V_{i,k}$

$V_{r,k}$: Annual volume of vehicles demanded by country r in body style k

$M_i = M_i + M_i \kappa$ if $V_i - J_i > 0$ (Overtime Manufacturing Cost / Vehicle for plant i)

$S_{r,s}$: Shipping cost from production country r to sale country s (per vehicle)

$T_{r,s}$: Tariff imposed when importing vehicle from country r to country s (% of vehicle cost)

γ_i : maximum number of body styles plant framing device can accommodate at plant i

β_i : Framing Device Expansion Cost Estimate (plant - specific)

Decision Variables :

$A_{i,j}$: Plant - Platform Production Index for plant i and platform j

(i.e., is platform to be produced at plant?); 1 = yes, 0 = no

$C_{i,k}$: Plant - Body Style Production Index for plant i and body style k

(i.e., is body style to be produced at plant?); 1 = yes, 0 = no

$V_{i,k}$: Plant - Product Allocation (annual volume) for plant i and body style k

(number of vehicles of a particular body style are allocated to a plant)

$P_{r,s}$: Annual volume to ship from production country r to sale country s

(number of vehicles produced in a country [at plants within the country] and shipped to another country)

F_i : Body Style Framing (forcing) variable

(i.e., is plant maximum framing capability [# of body styles] exceeded, driving step - function increase in capital investment)

Model Formulation

Minimize:

$$Z = \sum_{i,j} A_{i,j} B_{i,j} + \sum_{i,k} (C_{i,k} E_{i,k} + F_i \beta_i) + \sum_{i,k} V_{i,k} M_i + \sum_{r,s} S_{r,s} P_{r,s} + \sum_{r,s} T_{r,s} P_{r,s}$$

Subject to the following constraints:

$$\sum_i V_{i,k} = \sum_s D_{s,k} \text{ for each body style } k$$

$$\sum_{i \in I_r} V_{i,k} = V_{r,k} \text{ for each country } r \text{ and body style } k$$

$$\sum_k V_{r,k} = \sum_s P_{r,s} \text{ for each country } r$$

$$\sum_r P_{r,s} = \sum_k D_{s,k} \text{ for each country } s$$

$$\sum_k V_{i,k} \leq K_i \text{ for each plant } i$$

$$\sum_j A_{i,j} \leq G_i \text{ for each plant } i$$

$$\sum_k C_{i,k} \leq H_i \text{ for each plant } i$$

$$C_{i,k} * \sum_r D_k \geq V_{i,k} \text{ for each plant } i \text{ and body style } k$$

$$A_{i,k} * \sum_r D_k \geq V_{i,k} \text{ for each plant } i \text{ and body style } k$$

$$C_{i,k} = \text{binary}, A_{i,k} = \text{binary}, F_i = \text{binary}$$

$$F_i * \beta_i \geq \sum_k C_{i,k} - \gamma_i \text{ for each plant } i$$

$$\forall i \in I_r, \forall k \in j$$

Model Description

The model's optimization minimizes manufacturing and logistics costs as described below:

- Capital investment to enable a plant to produce a product family (platform)
- Capital investment to enable a plant to produce a specific vehicle (model)
- Labor cost to build vehicles assigned to each plant

- Shipping cost of vehicles from producing plants (countries) to demand points (countries)
- Tariffs incurred when shipping vehicles from producing plants (countries) to demand points (countries)

The optimization is subject to the following constraints:

- The number of vehicles produced summed across all plants, by body style, must match the number of vehicles, by body style, required across all demand points (countries)
- The number of vehicles produced summed across all plants in a particular country, by body style, must match the total number of vehicles of the body style produced in that country
- The number of vehicles produced in a particular country, summed across all body styles, must match the number of vehicles shipped from that country (vehicles produced and sold in the same country are considered “shipped” with a shipping cost of zero)
- The number of vehicles shipped from all producing countries to a country demanding vehicles must match the number of vehicles, by body style, demanded for sale in that country
- The number of vehicles produced at a plant must be less than or equal to the plant’s annual overtime capacity
- The number of platforms produced at a plant must be less than or equal to the plant’s maximum platform production limitation
- The number of body styles produced at a plant must be less than or equal to the plant’s maximum body style production limitation
- Any plant producing a specific platform of vehicle must either already have the equipment and tooling for that platform installed at the plant, or must pay to have the necessary equipment and tooling added to the plant
- Any plant producing a specific body style of vehicle must either already have the equipment and tooling for that body style installed at the plant, or must pay to have the necessary equipment and tooling added to the plant
- Plants either have the capability to produce vehicles of a particular platform, or they don’t (a binary variable)
- Plants either have the capability to produce vehicles of a particular body style, or they don’t (a binary variable)
- A plant’s maximum body style limitation (# of body styles which can be produced at the plant) is directly influenced by the plant’s framing sub-system. This limit can be exceeded if the plant purchases additional framing capability, up to a new user-defined limit. The variable driving this step-function increase in body style framing capability is binary, meaning that the plant can either accommodate body styles up to its existing framing limit, or it can accommodate up to a user-defined limit with an additional capital investment.
- All plants are located in a particular country, defining shipping costs and tariff requirements
- All body styles are derived from a single platform (product family) and “belong” to that platform

Discussion of Model Formulation

One key piece of the model formulation is the estimate of capital (manufacturing) investment that must be made at a particular plant in order to produce a particular product. Each estimate has essentially two parts: a platform and a body style investment cost for each differentiated body style at each of the manufacturer’s plants. A plant must have the ability to produce both the “platform” and the “body style” associated with each model, thus the investment estimates reflect the plant’s current capabilities, as well as estimates of what it would cost to augment those capabilities to include other product platforms and

body styles. The estimates can be either generic (high-level) or specific to the particular plant; in other words, as a first cut, the manufacturer could assume that adding any platform to any plant where that capability does not exist will cost \$X M, and that adding a particular body style to any plant will cost \$Y M, rather than detailing separate cost estimates for each plant in his manufacturing system.

A plant that will produce a new vehicle then must first “purchase” the required tooling and equipment associated with the product platform (if the product is not based on a platform that plant currently builds), then “purchase” the tooling and equipment necessary to produce the specific vehicle. At a high level, this methodology reasonably reflects the reality of manufacturing investments in an automotive assembly plant. Vehicles often share common underpinnings which are produced for multiple body styles, and there are body-style-specific tooling and equipment (investment) requirements (even if similar vehicles of the same product family are already produced there). Moreover, a plant adding a new product family (platform) can be expected to have a much more significant manufacturing investment (than a plant adding a body style based on a platform already in production at the facility) due to the typical differences between platforms, and the necessary tooling and equipment to enable production of the new family of vehicles.

Several model constraints are of particular importance to the evaluation of a complexity threshold. In particular, the number of platforms and body styles allowed at a plant can be constrained. These two elements are primarily responsible for the operational complexity seen at a plant, and the user’s ability to limit them enables the comparison of constrained and less-constrained solutions. This concept will be covered in more detail in the next section.

Step-function increases in capital investment for hard “break points” are incorporated into the model at the plant level, specifically for adding style capability and capacity. For instance, if a particular plant can build up to 4 body styles at the nominal capital cost, but adding the 5th will require a step-function increase in investment, the model reflects this step-function. Additionally, nominal plant capacities are entered as constraints, based on typical 2 shift/5 day operations, but the model has the option to “buy” extra capacity at estimated overtime rates, as appropriate.

Labor rates do in fact differ at different plants, especially when including plants across several countries or regions. Thus, differential labor rates can be included in the model to add further reality to the cost minimization function to produce the entire portfolio of products. As formulated, labor expenses are treated as variable costs, but can easily be shifted to fixed-costs, which may be a more reasonable assumption in some circumstances, given the long-term and relatively inflexible nature of union contracts in the automotive industry. The model can then be used not only to optimize allocation among the manufacturer’s plants, but to determine which plants are most cost-effective to operate given different product volume scenarios.

An Example Model – Optimization Scenario

The model can be used to develop insight on the extent to which a complexity threshold may become a constraint for the firm as it develops its manufacturing strategy and tactical operating plans. By analyzing a number of scenarios for new product introductions (additional market entries, and thereby additional vehicle styles to produce in an existing or new facility), it is possible to develop order-of-magnitude estimates for the value of changing the most complexity-related constraints in the system: the number of platforms and body styles that may be produced at a particular plant.

New Product Entries from Two Platforms: Capital Investment

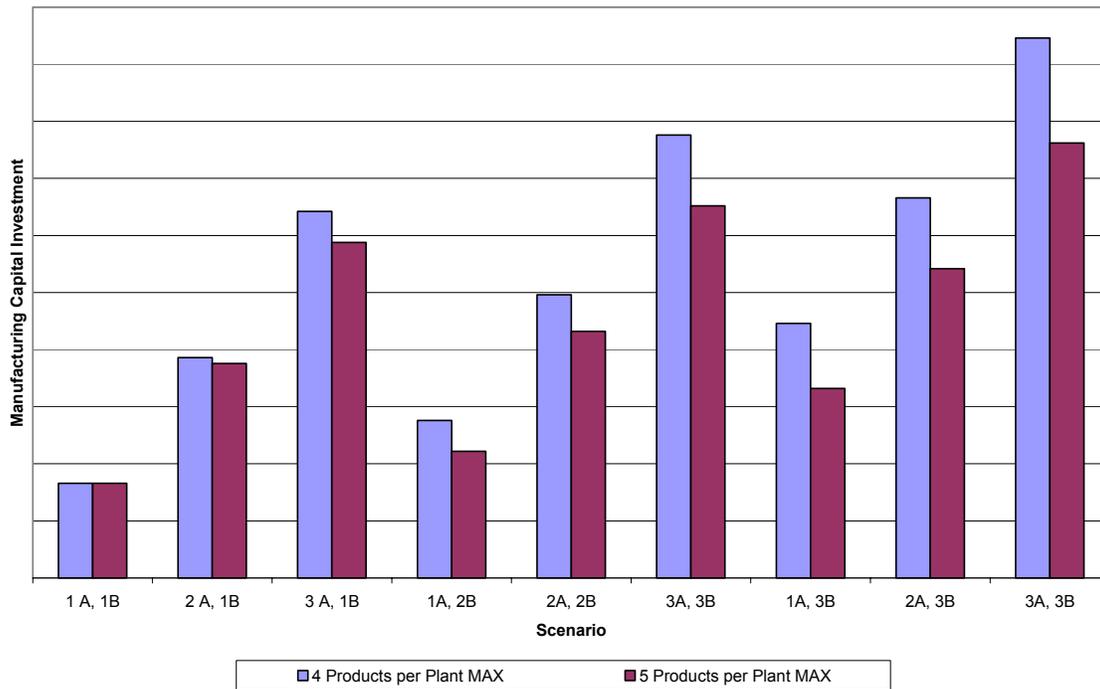


Figure 16: Modeling Analysis – Optimization Results

An example will help explain the logic here. Assume that a firm wants to introduce up to six new vehicle models, all based on either of two of its existing product platforms (referred to as Platform A and Platform B). Suppose further that the firm estimates demand for these vehicles to be approximately 50,000 units per year. Then, the manufacturer must determine where to build these 50,000 – 300,000 vehicles (annually) to minimize its total cost of production, thereby maximizing its profits.

[We assume here that the marketing and forecasting departments have done their homework to determine that anticipated revenues from these vehicles more than offset the anticipated costs of developing and producing them. Ideally, the business case analysis is done in tandem with the manufacturing planning organization, which can give input on the likely scenarios for what it will cost to build the vehicle, given the other programs being produced at the time].

The optimization is run multiple times with different complexity-related constraints. In this example, we develop a manufacturing cost (capital investment only; labor costs omitted to simplify calculations) estimate for the production of the vehicles separately for each constraint of four and five body styles in any one plant. Then, the outcomes are compared. Note that the six new models are counted based on whether they are based on Platform A or Platform B, and are simply summed along the x-axis. For instance, the right-most bar in Figure 17 refers to the production of three models based on Platform A, and three models based on platform B, and the left-most refers to production of one model based on each platform.

The optimization model estimates the impact of imposing a complexity threshold of the maximum number of body styles (unique vehicles, with all of their associated differences in structure, content, etc.) that can be produced in a plant. Not surprisingly, by relaxing this constraint from four vehicles to five,

the model is able to improve the optimization result to reduce capital expense. This makes intuitive sense; a plant with available capacity can most cost-effectively produce a vehicle that is similar to what is already being produced at the plant, i.e., one designed and built from the same underlying platform. Thus the model attempts to place like-platform vehicles into the same plants, up to their body-style (and/or annual capacity) limitation. When these limits are reached, the model must assign new vehicles to plants currently producing vehicles designed on a different platform, or move existing models to different plants. This is more expensive due to the differences in vehicle locating schemes, processing requirements, content differences, etc. between vehicles not based on the same underlying platform.

It is, however, reasonable to expect that producing the $(n+1)^{\text{th}}$ style in a plant will result in some level of operating impact: perhaps decreased labor productivity, increased kitting and sequencing costs, increased material storage and logistics costs, etc. Quantifying and estimating these costs are quite difficult, based on the number of plant-specific considerations that must be factored into the analysis, and thus is not included as part of this model. Thus, a direct comparison of capital savings to operating cost increases is not possible, based on the data available to construct this model.

Shadow Price Analysis

The above analysis is complemented by reviewing the shadow prices developed by the optimization model. The Excel-based optimization program will produce an analysis report including shadow prices; these shadow prices reflect the value (or cost) associated with a marginal unit of the particular constraint. For instance, in the case of the plant's body style complexity limit (a user-defined input constraint, based on the plant's framing limitations), the shadow price associated with this constraint will tell the user the value of having increased the plant's complexity limit by one body style. Or, in the case of the plant's platform limit, the shadow price will tell the user the value of being able to produce an additional platform at the particular plant. [This value will be developed in terms of the overall manufacturing cost of the vehicles being allocated and produced by the optimization model, including both capital and operating costs.]

This shadow price information can be quite helpful in the overall manufacturing planning process, as decisions to incorporate additional plant capability, whether in terms of body style capabilities, platform capabilities, or plant unit capacities, are often made for the marginal case: for instance, shall the manufacturer add the capability to produce one additional body style at this particular plant? Using the model's output and shadow price information, the planner can determine the value of making such a decision, and balance that against the costs associated with the capability.

Tolerance of Added Complexity-Driven Operating Costs

Alternately, the notion of making a trade-off between capital investment savings and operating cost increases (associated with the addition of new vehicle body styles to a manufacturing facility) can be used to develop insight about the tolerance of operating cost impacts. The decreased cost of the manufacturing plan associated with a relaxation of the "complexity constraint" (number of body styles in a plant) is the amount of operating complexity that the firm should be willing to tolerate at the manufacturing facility, all else being equal. In other words, if the firm can save \$100M in capital and/or production expenses by enabling a plant to produce five body styles rather than four (including the cost of adding the tooling and equipment necessary for the 5th style at the plant), then it should be willing to tolerate perhaps up to \$100M in added operating expenses (not considering depreciation effects of the capital investment and the net present value terms of the operating costs over time) in order to execute this strategy.

If it anticipates less than \$100M in operating cost differential for adding that 5th style to the plant in question, over the course of the vehicle program's lifetime, then the marginal decision is clear: allocate capital to enable 5-style production at the plant, and follow the recommendation of the optimization model to realize the most cost-effective manufacturing strategy for the new vehicles.

This series of scenarios can be repeated over and over, utilizing different possibilities for new products and the platforms they are based on. The results generated can inform the macro manufacturing strategy of how to transition the plant footprint and capabilities over time to meet market demand for a greater number of lower volume vehicles. As well, the results inform the tactical picture for which plants make sense to add particular vehicle programs in the short to medium term.

Thus, rather than developing a hard "rule" for the amount of complexity that a vehicle assembly plant can accommodate, this approach makes use of an optimization tool to analyze marginal scenarios and determine the most cost-effective way of meeting production requirements (based on estimates of the associated capital investment and operating costs). By manipulating the complexity-related constraints, the planner/strategist is able to understand the value of implementing a high- or low-mix (body style) manufacturing plan at a given plant, series of plants, or indeed, across the entire manufacturing system. This value can then be compared to the best estimates of operating complexity impact that will be experienced by the plant(s) in building their allocated products, and an effective decision made about where to spend capital improvement dollars, considering both the costs and benefits of complexity.

As an illustration, a first-cut analysis to look at the change in operating expenses at the plant level would include estimates for the changes in labor productivity, kitting and sequencing costs, and indirect/overhead expenses. For illustrative purposes, assume a vehicle requires 20 hours of labor at \$60/hour (near the fully burdened UAW rate), and requires kitting and sequencing operations at a cost of \$100 per vehicle. Then anticipated changes from these values are used in the comparison with the anticipated capital investment savings realized through a higher-mix manufacturing strategy at a particular plant (or series of plants).

The logic developed is clear: strategists in the manufacturing planning organization can utilize this tool to develop estimates of anticipated manufacturing cost savings associated with higher-mix strategies. They can then look at the specific instances of the plants affected and determine whether there will be operating impacts in labor productivity, overhead (kitting and sequencing, additional material coordination and storage, etc.), or other areas that would drive them to reduce the maximum complexity threshold at this particular plant, or across a series of plants. If not, then the capital allocation suggested by the model (or as modified by the strategists and planners) can serve as the basis of the forward-looking manufacturing plan.

Additional constraints can be added to the model (either at specific plants or across the wider manufacturing system) to force the consideration of the operating cost impacts anticipated. The added constraints force the optimization model to find a better solution based on this new information. In this way, a result can be iteratively developed until the strategists are satisfied with the optimization results.

Suggested Future Model Extension: Effects of Uncertainty in Volume Estimates on Manufacturing Strategy and Plant Complexity Evaluation

The model's capabilities can be extended further to include the assessment of uncertainty associated with vehicle production forecasts. This can be accomplished by utilizing the linear program allocation model

inside of a monte-carlo based optimization model. The monte-carlo model can represent the production forecasts as normal (or other) distributions, followed by an optimal allocation (linear program), then followed by a simulation of realized demand (monte-carlo forecasts). This will enable the valuation of not only the best capital and production allocation strategies to a single point forecast for volume, but across a range of likely volume scenarios. Thus, the result will be much more robust to the uncertainties in product demand that are a part of the market for motor vehicles. Further, analysis can be performed to determine how sensitive the optimal allocation is to demand uncertainty.

Alternately, a recourse-based modeling strategy can be utilized to bring the consequences of demand uncertainty to bear on the capital investment/allocation decision process, similar to the methodology proposed by Petruzzi and Dada, and by Cattani, et al.^{30 31}

The capability to evaluate the impact of uncertain demand will additionally enable the financial evaluation of flexibility initiatives in the context of manufacturing allocation and complexity. For instance, a flexibility initiative that enables a cost savings associated with shifting different products into or out of a plant can be added to the model, to some or all of the manufacturing facilities. The capital investment associated with the flexibility initiative can then be weighed against the benefits it helps to achieve in meeting cost minimization targets to produce the range of vehicles that customers actually demand (through demand uncertainty simulation), rather than basing this investment decision solely on point forecasts, which are inherently inaccurate.

Learnings

Two key learnings were developed in the effort to understand the cost of complexity through modeling. First, rough cost estimates for the production of particular product platforms and body styles at specific plants had to be developed from existing data and knowledge. While these figures are certainly “round” numbers, they serve as a starting point when considering where to build a new vehicle, or perhaps where to re-allocate (ie, move production of) an existing vehicle currently in production.

Most importantly, as the optimization model’s output is only as good as the fundamental data on which it relies, it became readily apparent that improved cost estimates were absolutely necessary to improve the fidelity of model output in the future. While parts of the organization recognized both the need for these cost estimates and the difficulty associated with developing them, this project’s attempts to analyze the cost of complexity shed further light on the need for obtaining and developing good cost data to support decision-making processes.

Second, there is a great deal of ambiguity regarding complexity in the assembly plant – it is difficult both to define and to readily obtain good data on the topic. However, if a manufacturer hopes to build a better understanding of how his operations are affected by complexity, paralysis is not an option – he must do something. Thus starting with a relatively simple framework and model for analysis may seem insufficient, as it ignores many factors and makes many assumptions. However, this starting point may be the doorway to breaking down a very complex problem into a simpler construct that can be understood. The construct can then be extended and expanded as data, information, and understanding is developed.

³⁰ Petruzzi and Dada.

³¹ Cattani, et al.

Conclusions

Deciding how many products to produce in a single assembly plant is critical to any manufacturer working to most effectively utilize its facilities. It is perhaps even more important when the manufacturer faces lower average product volumes due to greater numbers of products on the market without a corresponding proportional increase in overall market volume. As the firm develops plans for its new products, it must consider where to produce them based on its current and future plant capacities and capabilities. This will directly inform the product planning organization concerning the cost to produce the anticipated new product, enabling the development of a sound business case analysis for the product's introduction.

Producing more vehicle body styles in a single plant increases the level of complexity that the plant must accommodate. Handling more and different types of materials flowing in from suppliers, differing assembly procedures, the need for dedicated production cells for particular elements, and the need to handle the product's differences by reusing of the existing equipment are just some of the complexity challenges.

There are costs and benefits associated with the production of more vehicles in an assembly plant. Higher utilization rates resulting from an added product enables the realization of lower unit costs. Producing similar vehicles (based on the same product platform) in the same plant(s) enables the sharing of capital-intensive tooling and similar build processes. Yet the added complexity brings with it a number of costs. Thus the firm must decide not whether there is an absolute complexity threshold to be adopted for all of its plants, but evaluate each marginal case of a new product introduction on its own merits.

Estimating the costs associated with higher levels of operating complexity (here, more body styles to build in a plant) is necessary but difficult. An analysis of direct measures of cost impacts did not enable sufficient separation of the elements contributing to these costs. Thus, an indirect approach was developed to allow cost thresholds to be identified that are associated with particular vehicle introductions into the manufacturing system. These thresholds then serve as the basis for evaluating the operating cost impacts anticipated in the production of more products in a given plant, or set of plants.

The organization can then evaluate whether it believes the operating cost impacts associated with a particular manufacturing allocation plan exceed the savings reached through the relaxation of complexity constraints (ie, the introduction of higher-mix strategies in one or a number of assembly plants).

The key insight developed here is that a single "complexity threshold", put together through an analysis of expected cost impacts of the higher-mix manufacturing strategy, is insufficient for the firm to determine its most optimal manufacturing strategy. Further, a single complexity threshold is insufficient to drive the information exchange that is necessary between product and manufacturing strategists and planners, as it ignores the relative nature of any marginal analysis, the idea that the best strategy is developed from an analysis of alternatives. Fixing a limit to complexity accommodation in any plant is likely to handicap an organization that otherwise may innovate and flexibly adapt to market pressures for products of a particular variety, and will not serve to fully inform the trade-off being made of revenues and costs.

A manufacturer can employ an optimization model, such as the one developed here, to determine the best plan(s) for production of vehicles, thereby giving it direction on which scenarios and plant allocations should be studied in further detail. The model acts as a capital allocation analysis and deployment tool by

looking for the most cost-effective plan to meet production requirements given the manufacturing system constraints. Ultimately, a plan to deploy capital investment to produce the vehicles is selected, based on input from the optimization and other required analyses.

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AutoSitePro Database

PriceWaterhouseCoopers Automotive OEM database

Ward's Automotive Database

Personal interviews with the following individuals at a major automotive manufacturer:

- Manager #1, Manufacturing Intelligence
- Staff Member #1, Manufacturing Intelligence
- Manager #1, Research and Development
- Manager #2, Research and Development
- Staff Member #1, Research and Development
- Staff Member #2, Research and Development
- Staff Member #3, Research and Development
- Manager #1, Corporate Strategic Initiatives
- Manager #2, Corporate Strategic Initiatives
- Staff Member #1, Corporate Strategic Initiatives
- Manager #1, Manufacturing Finance
- Staff Member #1, Manufacturing Finance
- Manager #1, Advanced Vehicle Development Body Center
- Staff Member #1, Vehicle Architecture
- Manager #1, Body Manufacturing Engineering
- Staff Member #1, Body Manufacturing Engineering
- Staff Member #2, Body Manufacturing Engineering
- Staff Member #1, General Assembly Center
- Manager #1, Industrial Engineering Productivity Support
- Staff Member #1, Industrial Engineering Productivity Support
- Staff Member #2, Industrial Engineering Productivity Support

Staff Member #3, Industrial Engineering
Manager #1, Manufacturing Engineering
Staff Member #1, Manufacturing Engineering
Staff Member #2, Manufacturing Engineering
Staff Member #3, Manufacturing Engineering
Staff Member #4, Manufacturing Engineering
Staff Member #5, Manufacturing Engineering
Manager #1, Manufacturing Planning
Staff Member #1, Manufacturing Planning
Staff Member #2, Manufacturing Planning
Director #1, Advanced Vehicle Development-Manufacturing Engineering
Manager #1, Advanced Vehicle Development-Manufacturing Engineering
Manager #2, Advanced Vehicle Development-Manufacturing Engineering
Manager #3, Advanced Vehicle Development-Manufacturing Engineering
Manager #1, Vehicle Operations