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The Impact of Product Variety on Automobile Assembly Operations: Empirical Evidence and Simulation Analysis

Abstract

This study examines the impact of product variety on automobile assembly plant performance using data from GM's Wilmington, Delaware plant, together with simulation analyses of a more general auto assembly line. We extend prior product variety studies by providing evidence on the magnitude of variety-related production losses, the mechanisms through which variety impacts performance, and the effects of option bundling and labor staffing policies on the costs of product variety. The empirical analyses indicate that greater day-to-day variability in option content (but not mean option content per car) has a significant adverse impact on total labor hours per car produced, overhead hours per car produced, assembly line downtime, minor repair and major rework, and inventory levels, but does not have a significant short-run impact on total direct labor hours. However, workstations with higher variability in option content have greater slack direct labor resources to buffer against process time variation, introducing an additional cost of product variety. The simulation results support these findings in that once each workstation is optimally buffered against process time variation, product variety has an insignificant impact on direct assembly labor. The simulations also show that bundling options can reduce the amount of buffer capacity required, and that random variation is more pernicious to productivity than product variety, supporting the efforts of some auto makers to aggressively attack the causes of random variation.

Keywords

product variety, assembly lines, auto industry

Disciplines

Accounting | Business Administration, Management, and Operations | Operations and Supply Chain Management

THE IMPACT OF PRODUCT VARIETY ON AUTOMOBILE ASSEMBLY OPERATIONS: ANALYSIS AND EVIDENCE

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We report results from a multi-year empirical study on the impact of product variety on automobile assembly plant productivity. Three sources of data were used to examine the research questions and triangulate the findings. First, we conducted field research in more than 20 assembly plants worldwide to study how they cope with product variety through manufacturing flexibility. Second, using time series and cross-sectional data from GM's Wilmington, Delaware plant, we examined the effects of product variety and the variability in work content per car on various performance measures. Consistent with the field evidence, the time series analyses indicated that greater variability in option content has a statistically significant adverse impact on total labor hours per car produced, overhead hours per car produced, downtime in the assembly line, minor repair and major rework, and inventory as a percentage of cost of sales. We also found that work stations with higher variability in option content have significantly higher slack resources to protect against variety-related defects and downtime, introducing an additional fixed cost of product variety. Finally, we used simulation to measure the impact on assembly line downtime of variability in work content per car. The simulation study confirmed the results of our statistical analysis.

1. Introduction

Ever since Henry Ford made his famous offer of “any color as long as it’s black,” a position on the right level and type of product variety to offer the consumer has been a cornerstone of most automobile manufacturers’ strategies. Variety has steadily increased throughout most of this century, starting with Alfred P. Sloan’s rejoinder to Ford offering “a car for every purse and purpose” that was supported by General Motors' strategy of segmentation by price and value. In the last two decades, further increases in variety have been fueled by European and Japanese competitors who introduced segmentation on size as well as popular niche cars like the Mazda Miata. The state the auto industry had reached by the start of this decade is well illustrated by a fact we learned during a 1991 visit to the Mazda Hiroshima Plant — the Mazda 323 is produced in this plant for worldwide markets in 180 different colors, including four shades of black, an ironic twist on Henry Ford’s original offer.

In the last few years, auto manufacturers worldwide have been retrenching on the level of variety they offer, in part to reduce costs during the recent recession. But whether variety has been increasing or decreasing, what remains constant is a general lack of understanding of variety's impact on manufacturing costs. The accounting and operations management literatures have emphasized the potential costs from increasing variety (e.g., Skinner, 1974; Hayes and Wheelwright, 1984; Miller and Vollmann, 1985; Cooper and Kaplan, 1991). Researchers in these fields argue that higher product variety creates considerable challenges for manufacturing operations. With an increasingly complex product mix comes additional parts, less accurate demand forecasts, greater inventory and material handling, additional setups, more complex scheduling and task assignment, greater chance of quality problems, and increased supervisory requirements. As a result, greater resources must be committed to handle the increasing number of transactions and manufacturing contingencies and ensure the smooth operation of the plant.

Although greater product variety is widely believed to be associated with higher manufacturing costs, empirical studies show mixed results. Research using the Profit Impact of Marketing Strategies (PIMS) data base found that significant market share benefits accrued from broader product lines, but observed no relationship between self-reported production costs and product variety (Kekre and Srivasan, 1990). Cross-sectional accounting studies by Foster and Gupta (1990) and Banker et al. (1993) also found little association between *direct* measures of product mix complexity (e.g., number of parts, number of suppliers, breadth of product line) and manufacturing overhead costs, *after* controlling for direct labor costs. In contrast, a time-series analysis of textile plant production costs by Anderson (1995) found that more heterogenous product mixes increased manufacturing expenses. In the automobile industry, MacDuffie, Sethuraman, and Fisher's (1996) cross-sectional examination of assembly plant productivity indicated that differences in parts complexity (e.g., number of suppliers, number of parts) negatively affected productivity, while model mix and product options had little impact. However, in plants employing "lean" production practices, parts complexity was not significantly correlated with productivity. Furthermore, Ittner and MacDuffie's (1995) study of auto assembly plants found that higher product variety had a significantly greater negative impact on overhead labor than on direct labor workers.

One explanation for the studies which found little or no impact on productivity from product variety is the fact that they examined cross-sectional samples, often using plants in different industries. Cross-sectional studies suffer from the limitation that different plants may not face the same cost or production function, even though cross-sectional estimation requires the assumption of common production functions. For example, some plants may have invested in flexible automation or other systems to limit the negative impact of variety, or variety/cost tradeoffs may differ depending upon industry or the *type* of variety being offered to the customer (e.g., fundamentally different products or peripheral differences in color, accessories, etc.). To the extent that these omitted variables are not included in the analysis, the results may be biased. In contrast, time-series studies of individual plants can address many of these limitations by holding technologies, capabilities, and production functions constant.

This paper reports the results of a multi-year study designed to better understand the impact of product variety on automobile assembly operations. We have examined three research questions: (1) Which dimensions of product variety have detrimental effects on manufacturing performance?, (2) What is the magnitude of productivity losses due to product variety?, and (3) What methods are available to minimize the adverse effects of variety? Our research began in 1991 with visits to more than 20 auto plants worldwide to study how they coped with product variety through manufacturing flexibility. Besides observing the manufacturing processes in these plants, we interviewed engineers and managers and examined company documents on the technology, systems and concepts used to achieve flexibility. We observed that plants differed greatly in the amount and type of variety with which they must cope. The best plants at coping with variety had achieved flexible capabilities in three areas: hardware (e.g., programmable welding robots and quick changeover paint booths), software (including computer software such as sequencing algorithms to control balance losses and materials requirements planning software to coordinate parts supply, and also organizational "software" such as procedures and decision processes that generate greater flexibility (like faster setup routines, Kanban systems for controlling work-in-process inventory, and management control systems that provide incentives to acquire and utilize flexible technology), and human skills (such as cross-trained workers and the hiring of more highly skilled workers needed to interface with flexible automation). Extensive reports of these field observations are provided in Fisher, Jain and MacDuffie (1995) and Ittner and Kogut (1995).

This paper tests and extends our field observations based on a three-year study of the General Motors Wilmington Auto Assembly Plant. Our project began with numerous visits to the plant to observe the production process and interview managers in order to better understand the relevant dimensions of product variety and how they impact plant productivity. The first author also worked on the assembly line for two days to understand how product variety impacts this process. Based on these activities, as well as our earlier field visits to auto plants worldwide, we formulated hypotheses on how variety impacts productivity. We tested these hypotheses using three sets of empirical data. The first set of tests examined the association between product variety and labor productivity, major rework, and inventory using monthly data over a 27 month period. The second set of tests took a more detailed look at variety's impact on direct labor productivity in the body, paint, chassis, trim and final assembly operations using data covering 151 production days. The third set used data from 71 work stations to examine the cross-sectional relationship between the amount of option variability and the level of slack labor resources in a work station in order to learn how buffers are used to shield operations from the adverse effects of product variety. Finally, we developed a simulation model of an automobile assembly process to conduct more directed ‘laboratory’ studies of how variety impacts assembly line labor productivity.

The remainder of the paper is organized as follows. Section 2 describes our research site. Section 3 summarizes our field observations on the nature of product variety at our research site and how it impacts plant processes. Section 4 describes the results of our empirical data analysis, and Section 5 of our simulation study. Our conclusions are provided in section 6.

2. Research Site

The General Motors Wilmington, Delaware assembly plant was built in the late 1940s, and currently employs approximately 3,500 workers producing 250,000 Corsica and Beretta model Chevrolets per year. The plant's production process (see Figure 2.1) begins with stamped body parts that are produced in Lordstown, Parma and Mansfield, all in Ohio, and shipped to the plant via rail. These parts are welded together in the body shop to create a car body that is then painted in one of ten colors. Both the body and paint processes are highly automated. To create a finished car, the painted body is assembled with numerous parts on a long, moving assembly line that snakes through the plant and contains approximately 600 work stations. The assembly line is divided into three sections: trim, chassis and final assembly. Lightweight parts, such as headlights and interior trim, are installed in the trim section, while heavier parts, such as the engine and transmission, are installed in the chassis section. Final assembly performs a number of small operations such as filling the various fluid reservoirs, making numerous quality checks and conducting minor repairs as necessary. The assembly line has a 60 second cycle time, implying that one car per minute rolls off the end of the line.

Most work stations are staffed by a single worker responsible for installing a specific part or parts. Parts typically come in several versions (e.g., different specifications or colors) and many parts are only installed on a subset of cars. Consequently, workers must check a manifest on the car to determine which part type, if any, is required. A work station's operation begins as a car approaches the point on the line where the worker is stationed. The worker determines the required part type, selects the appropriate part and required tools from a lineside storage area, walks to the car and installs the part. Since the line moves continuously, the worker is required to walk along side the moving car as the part is installed. When the operation is complete, the worker walks to the next car to begin the next operation.

The time to perform an operation can vary from car to car, and some cars may not require a specific operation at all. It is not feasible in the long run for the average operation time to exceed the one minute cycle time. However, the time for a *single* operation can exceed one minute if the preceding and/or following operation requires less than one minute to complete. In these instances, a worker makes up the time for an operation that requires more than one minute by starting early and/or finishing late, borrowing time from preceding and following cars.

The assembly process is extremely complex and involves the installation of several thousand parts. Many things can go wrong during the approximately 22 hours required for a car to move through the plant. A typical problem on the assembly line is the inability to install a part correctly, either because the correct part is not available or deviates from specifications, or because an earlier step on the car was performed in such a way that the current operation is impossible to perform. If a problem occurs, the assembly worker will generally try to rectify the problem within the one minute cycle time. If this cannot be done, the choices include pulling a cord to stop the line, thereby allowing the problem to be fixed while the line is down, or noting the problem so it can be fixed in final assembly or in an off-line major rework area.

The assembly line is supported by the parts supply process. This process starts with a supplier plant producing a part and ends with the part arriving in an assembly line worker's hands just as the car requiring the part enters the work station. Supply plants are provided with the daily build schedule via an electronic data interchange network, with sufficient leadtime provided to allow delivery of the required parts when they are needed.

The Wilmington plant has steadily increased its use of Just in Time (JIT) supply relations. Three types of JIT relationships are maintained by the plant. Delaware Seat Company illustrates the closest type of relationship in which a supplier produces and delivers JIT. Because Delaware Seat is located only five miles from the General Motors plant and has developed an extremely flexible manufacturing process, they are able to receive the seat specifications for a car as it is loaded on the line, and then, as the car moves down the line, produce the required seat and deliver it to the line by the time the car reaches the seat installation work station about 4 hours later. The second type of relationship is to deliver JIT without JIT production. Struts, for example, are delivered four times a day in response to immediate needs from an inventory maintained at the strut supply plant. GM keeps only a few hours of strut supply within the assembly plant. The third type of JIT delivery is illustrated by steering columns, which are delivered based on the previous day's usage, which requires the GM plant to keep a buffer stock of about one day's supply of steering columns.

"Parts presentation" refers to the process for moving parts within the plant so as to place the right part into a worker's hands just as the car requiring that part appears before the worker. The plant uses various methods of parts presentation depending on the variety of parts used at a work station. If variety is low, inventories of the different parts are maintained at line side and a worker simply selects the appropriate part from inventory as required. For example, if only two types of floor carpets were used, stacks of these two types of carpet would be placed next to the worker, who would select the appropriate carpet as each car arrived. As the number of carpet types increases, the time for a worker to identify and pull the required carpet steadily increases. Eventually, it becomes more economical to keep a single stack of carpet next to the worker that contains all of the carpet required in the next couple of hours, sorted according to the sequence of cars that will be arriving at that work station. The sequencing of the carpet stack is done by material handling workers who can be more efficient at sequencing than the assembly worker because they use a dedicated batch process. For bulky high variety parts, a conveyor line is used to carry the parts to the assembly line in the sequence they are required. For example, facia are molded plastic parts that go on the front and rear of the car and have high variety because of different colors, requirements for a trim strip, etc. Facia are assembled and sequenced in a separate process and transported to the installation station via an overhead conveyer.

Plant labor is classified into direct and overhead categories, with overhead including both indirect and salaried labor. Direct labor consist of line workers who actually add value by placing parts on the car. Indirect labor includes a variety of off-line workers involved in material handling, maintenance, inspection and major rework, as well as a set of workers called "trainers" who are skilled in a variety of assembly line tasks and positioned near the line to assist line workers if they experience problems that threaten to take more than the one minute cycle time to resolve. Salaried labor includes supervisors and plant management and administration personnel. Through increased use of JIT, better presentation of parts to workers, and a continual effort to eliminate all forms of waste, this plant has achieved the highest labor productivity in the General Motors system.

3. How Product Variety Impacts the Production Process

Cars vary along several dimensions, including body style, exterior and interior color, power train specifications and choice of options. As shown in Table 3.1, each type of variety affects a different part of the production process. The greatest variety occurs in those dimensions that impact only the assembly and parts supply processes: interior color, power train specifications and choice of options. Product variety is not a critical issue for the body shop and paint processes, since these processes are highly automated and sufficiently flexible to handle the limited variety with which they are presented at little or no labor cost penalty.

The assembly line is impacted by product variety through variability in the operation times at work stations along the assembly line. To mitigate this effect, most auto plants sequence cars on the assembly line to smooth average workload. For example, if 25% of the cars require a sunroof, then in the ideal sequence, every fourth car has a sunroof. As discussed before, workers can usually accommodate a longer operation time if it is preceded and/or followed by shorter times. However, the ideal sequence for one work station is probably not ideal for other work stations, which limits the ability of sequencing algorithms to eliminate the negative impact of operation time variability. As a result, workers frequently encounter an operation time that is too long to be completed within the allotted cycle time, causing either a line stoppage to finish the operation or an uncompleted operation that is left to be completed either in the final assembly process or in major rework. Consequently, our field observations lead us to predict that higher product variety increases downtime, minor rework done in final assembly, and major off-line repairs.

Our field research also suggests that the adverse impact of product variety on downtime and rework can be reduced by assigning a lower average workload to work stations that are subject to higher amounts of operation time variation. The difference between the one minute cycle time and the average operation time assigned to the work station becomes a buffer for absorbing variation in operation time, minimizing the productivity losses from downtime or rework. However, the addition of buffers to the assembly process may do little to shield overhead workers and the parts supply process from the adverse effects of product variety.

Product variety affects the parts supply process throughout the chain from the parts supply plant to the assembly worker's hands. Greater part variety implies lower volume per part, which raises parts production costs. In addition, statistical process control becomes harder to perform when demand for parts is low and episodic, increasing the number of quality problems. More parts and lower volume per part also increase the coefficient of variation in demand for any particular part, requiring greater safety stocks and an increased risk of stockouts. The costs of potential stockouts include additional overhead labor to expedite parts, as well as the costs of line stoppages, rework, and quality problems due to actual stockouts. The time for an assembly line worker to access the correct part also goes up with product variety, increasing the risk that the worker will choose the wrong part, resulting in rework and quality problems.

A distinction between fixed and variable costs is useful here. Downtime and rework are variable costs of variety because they vary day-to-day depending on the level of variety in each day's build schedule, whereas the idle time planned for a workstation as a buffer against mix variability is a fixed cost in that it is incurred every day independently of the level of product variety on that particular day. The classification into fixed and variable costs of variety is particularly useful for the parts supply process. Fixed costs of variety include investments in information systems to determine how much of each part is required each day and to communicate this information to all suppliers, sequencing algorithms to space out options, investments in JIT production and delivery systems by suppliers, and parts presentation systems such as off-line kitting operations or parts conveyor systems. Generally, as variety increases, fixed cost investments in systems to deal with variety become more economically justifiable. This is illustrated in Figure 3.1 for the process of presenting a part to a lineside worker. If variety is low, the worker can simply select from lineside inventories. As variety grows, investments in off-line kitting operation and, eventually, conveyors to transport parts to the line become justified (especially when parts are heavy or bulky). Each of these investments decreases the *variable* cost of variety but increases the *fixed* cost. Once the plant reaches a high level of variety (e.g., when the plant invests in a parts conveyor line in the example depicted in Figure 3.1), the *variable* cost of variety can be so low that small changes in the level of variety appear to have little or no impact on *labor* costs, disguising the fact that the plant is paying a high cost for variety in the form of fixed investments in variety-related handling systems.

4. Empirical Results

Our empirical tests focus on the variable labor costs of product variety and the fixed costs arising from slack labor resources held to minimize variety-related production problems. Because fixed investments in variety-related systems or other automation did not change significantly during the period under study, they are not considered in the analyses. We use three sets of data to conduct our tests: (1) monthly data for 27 production months, (2) daily data for 155 production days, and (3) cross-sectional data for 71 work stations in the chassis and trim operations.

4.1 Monthly Analyses

Our first set of empirical tests examines the impact of product variety on plant-level labor productivity over a 27 month period. The dependent variables in our analyses are the number of *paid* total, overhead, and direct labor hours per car produced, the percentage of cars requiring major rework, and the level of inventory as a percent of cost of sales for the month.

We examine two product mix variables: (1) the average level of option content on the cars produced that month, and (2) the standard deviation in option content per car.[1]

Option Content. This variable equals the number of options on an average car from the following list of 8 options: power door locks; power windows; cruise control; luggage rack/spoiler; sun roof; two-tone paint; six cylinder engine; and five speed transmission. The percentage of cars carrying these options is regularly reported to management due to their potential disruptive impact on production. Let μ_i denote the fraction of cars that have option *i*, *i* = 1, ..., 8.

The mean option content then equals μ_i.

Option Variability. Our option variability measure equals the standard deviation in the number of options per car. For *i* = 1, ..., 8 and a randomly selected car, the variable

$$x_i = \begin{matrix} 1, \text{ if option } i \text{ included} \\ 0, \text{ otherwise} \end{matrix}$$

is a random variable with mean μ_i. However, because options are often bundled, the x_i are not independent which complicates computation of the standard deviation. Based on our discussions with plant management about option bundling practices in the plant, we assume an inherent hierarchy in the handling of options. If $\mu_{i1} \geq \mu_{i2}$, then any car with option i_2 is assumed to have option i_1 as well. With this assumption, we can compute the fraction ρ_i of cars that have exactly *i* options. Assume for notational simplicity that $\mu_1 \geq \mu_2 ... \geq \mu_8$. Then:

$$\rho_i = \mu_i - \mu_{1+i}, \quad i = 1, \ldots, 7, \quad \rho_8 = \mu_{8,} \text{ and } \quad \rho_o - 1 - \quad \rho_i - \mu_1$$

The standard deviation in the number of options per car equals

[1] We also examined the effect of model mix (four-door Corsica or two-door Beretta) on the dependent variables. Greater production of the larger Corsica had a statistically significant negative impact on total and overhead labor productivity but not on the other dependent variables. Moreover, the results for the other independent variables changed little from those reported in the paper. Given the already small sample size, the ratio of Corsica to Berettas is not included in the reported results for the monthly tests.

The Option Content and Option Variability measures have a correlation of -0.31 ($p < 0.01$, two-tailed), reflecting the reduction of option variability that occurs as more options are included as standard equipment.

In addition to the product mix measures, three control variables are included in the empirical tests:

Capacity Utilization. Since staffing for many overhead functions is relatively fixed in the short-term, a capacity utilization variable is introduced to separate movements in labor hours per car that are due to volume changes from those due to efficiency changes. The capacity utilization measure is defined as the number of cars scheduled for production that month divided by the plant's theoretical capacity in cars for the month.

Body Shop Uptime. Body shop uptime represents the percentage of available production time that the body shop is operating. Body shop downtime is primarily due to mechanical problems that are independent of the product mix produced by the plant. Because all downstream operations are dependent on the body shop for the basic infrastructure of the car, these operations are idled if the body shop is down for any length of time, lowering overall plant productivity. Consequently, labor hours per car should be negatively related to body shop uptime.

Startup Month. The Wilmington plant was shut down for one month during the period under study. In the following startup month, direct labor staffing was at normal capacity levels, but actual production levels were intentionally held down to minimize startup problems. This variable controls for the lower labor productivity during the startup month. The measure is coded one for the startup month and zero otherwise.

Descriptive statistics for the 27 months covered by the monthly analyses are provided in Table 4.1. The total number of hours per car ranged from 29.03 to 57.81, with a mean of 35.00. The number of options per car (from the list of 8) was 2.46, and the mean standard deviation in the number of options per car was 2.15. Body shop uptime ranged from 77.69% to 97.88% (mean = 87.61%), with the major rework rate averaging 1.90% over the 27 months. The ratio of inventory to cost of sales varied from 0.12 to 0.72 (mean = 0.26).

Table 4.2 provides the results from the monthly analyses. To control for autocorrelation, the models are estimated in first differences. Durbin-Watson and Box-Pierce *Q* statistics indicate that the remaining residuals approximate a stationary, white noise process. Moreover, autocorrelation and partial autocorrelation correlograms reveal no spikes to suggest any remaining systematic autoregressive or moving average component to the residuals.

Columns 1 through 3 examine the impact of product variety on labor hours per car. The adjusted R^2s range from 0.38 for overhead labor to 0.86 for direct labor. As predicted, direct labor hours per car are negatively correlated with body shop downtime and positively correlated with the startup month indicator. Total and overhead labor are lower when capacity utilization is higher, supporting the notion of economies of scale in fixed overhead resources. More importantly, the evidence indicates that greater option variety adversely impacts overhead productivity but *not* direct labor. These results are consistent with Ittner and MacDuffie's (1995) cross-sectional study of auto assembly plants, which found that the number of options had a significant negative impact on overhead hours per car, but was not significantly related to direct labor requirements. While a car with more options clearly takes more time to assemble, our results suggest that *paid* direct labor hours does not vary significantly with the number of options, an issue we investigate further in later sections. Our findings do support claims in the management accounting and operations management literatures that greater product variety increases overhead requirements. The coefficients on option variability in the total and overhead labor models imply that reducing option variability by 10% from its mean value reduces the number of hours required to assemble a car by slightly more than one hour.

The evidence indicates that the negative consequences of option variety are related more to the variability in option content rather than the mean number of options per car, a result consistent with our field observations. If every car came loaded with all options, production planning, material handling, and assembly procedures would be relatively straightforward. When variability in option content is introduced into the plant, however, planning and scheduling becomes more complex, sequencing and delivering the right parts to the line at the right time becomes more difficult and the possibility of assembly errors increases, leading to higher overhead requirements.

Columns 4 through 6 of Table 4.2 examine the extent to which increases in major rework account for the lower labor productivity in months with higher option variability. As shown in Column 4, major rework as a percent of production is positively correlated with option variability and negatively related to capacity utilization. The coefficient on option variability in the major rework equation implies that reducing option variability by 10% from its mean value lowers major rework by .158 or 8.3% from its average value over the 27 months. This evidence supports our field research which indicated that greater option variability increases assembly defects. Wilmington plant management indicated that the *negative* relation between capacity utilization and variability reflects the fact that defects tend to decline with longer production runs. Since major rework is performed by overhead personnel, it is not surprising that an increase in the rework rate significantly increases overhead labor (Column 6) but has little impact on direct labor (Column 5). The significant positive coefficient on option variability in equation (6) shows that option variability's impact on overhead functions extends beyond the additional overhead requirements caused by increased major rework.

The relationship between product variety and inventory levels (as a percent of cost of sales) is investigated in Column 7. Once again, the coefficient on option variability is positive and statistically significant while mean option content continues to show no significant relationship with the plant performance measures, supporting claims that higher product variety increases inventory requirements. The coefficient on option variability indicates that reducing variability by 10% from its mean lowered inventory as a percent of cost of sales by 0.0215, or 8.27% from its mean value. Additional analyses (not reported) indicate that the positive association between inventory levels and option variability is due both to the increased number of cars in the major rework area when variability is high, as well as to other variety-related factors such as increased inventory requirements and contingencies.

4.2 Daily Analyses

The monthly analyses suggest that product variety impacts overhead labor per car, but is not significantly associated with direct labor content. Our discussions with plant management indicated that the insignificant associations between the product variety measures and direct labor in the monthly tests is due in part to the availability of slack resources in direct labor operations. Our direct labor measure represents the number of *paid* direct labor hours per car produced.

If the number of cars scheduled to be produced in a standard eight hour shift is less than the plant's theoretical capacity, it may be possible to meet the shift's production schedule, for example, in seven and a half hours, with assembly workers being paid for the entire eight hour shift. If assembly problems are encountered, and the same production schedule takes anywhere between seven and a half and eight hours to complete, no additional expense is incurred. Only when production time is increased to more than eight hours is overtime required and direct labor workers are paid for more than eight hours. Consequently, direct labor hours paid and hours worked may not have a direct correspondence.

To examine this issue more closely, we gathered detailed production and direct labor data for 151 production days. The plant provided us with the specific options included on every car built during the period, *paid* direct labor hours in each assembly operation (body shop, paint, chassis, trim, and final assembly), and total production line downtime. We calculated mean option content and option variability based on 55 options (including two-door versus four-door) that the plant uses in its assembly line sequencing algorithm. The variety measures reflect only those options impacting the respective assembly operations (i.e., an option that affects work content in chassis but not in trim is not included in the trim operation's variety measures). Two control variables are included in the analyses: an indicator variable for the two production days following a plant shutdown, and body shop downtime. The models are estimated in first differences to control for autocorrelation.

Product variety's impact on the body shop, paint process, and three assembly operations is examined in Table 4.3.[2] The strongest determinant of paid direct labor hours per car is downtime in the body shop, which idles the entire assembly line. The only variety measure that is statistically significant is the *negative* coefficient on option variability in the body shop. This negative relationship appears to reflect the fact that option variability in the body shop is primarily due to the mix of two and four door cars, with the smaller two door bodies requiring less time to build. The correlation between option variability and the percentage of two door cars is -0.54 ($p < 0.01$, two-tailed), suggesting that the body shop option variability measure is proxying for differences in work content. Overall, the results in Table 4.2 are consistent with the monthly analyses, which found no relation between paid direct labor hours and product variety.

The insignificant relationship between paid hours per car and variety does not imply that variety has no effect on direct labor operations. Table 4.4 investigates the impact of option variability on production downtime and final assembly, where minor repairs are conducted. The results indicate that greater option variability in the chassis and trim operations leads to higher production downtime, even after controlling for downtime in the body shop. Similarly, variability in chassis and trim are positively related to direct labor hour per car in final assembly due to increased minor repair. These results support our field observations which indicated that product

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[2]The product variety measures used in the daily analyses relate to the *number* of options per car. We also repeated the analyses using product variety measures that were based on the standard *times* required to install the various options. The results were similar to those using the number of options, but the significance levels for the variety coefficients and the adjusted R^2s for the models were somewhat lower. Daily scheduled production data were not available, so the capacity utilization measure used in the monthly analyses was not included in the daily models. However, the minimal association between capacity utilization and direct labor in the monthly analyses suggest that this is not a major problem.

variety is a bigger problem in the chassis and trim operations than in the other assembly operations. The somewhat contradictory results in Tables 4.3 and 4.4 suggest that the slack direct labor resources built into the production schedule have generally allowed the plant to compensate for variety-related contingencies without paying overtime, thereby breaking the link between product variety and *variable* direct labor costs.

4.3 Work Station Analysis

If direct labor slack or buffers are being used to compensate for the adverse effects of option variability, we should see larger buffers in work stations facing greater option variability. We examine this hypothesis using data from 71 work stations that experience some variation in work content. A work station is defined as the work performed by one person on each car moving down the line. Each station performs "base" work on each car plus some combination of options. The standard time for a work station to perform an operation represents the expected work content (in fractions of a minute) to complete the required work on one car. A car passes each station once a minute, thus the cycle time equals one minute ($t = 1$). Slack time per car is defined as the one minute cycle time minus the standard time (in fractions of a minute) for that car. Slack time, standard production time per car, and standard deviations in standard times per car were calculated for each station over a month and a half time period. During this period, 15,958 cars were produced. Total slack time for the station over this period was then computed as follows:

The following regression results were obtained when direct labor slack time was regressed on variability in work content:

$$\text{Slack Time} = 4184.2 + 17291.0*(\text{Standard Deviation in Work Content})$$

The regression slope coefficient has a t-statistic of 4.43 ($p < 0.01$, two-tailed) and the adjusted R^2 is 21%. As predicted, this evidence indicates that work stations with more variability in option-related work content have more slack resources to compensate for this variation. These results support our field observations which indicated that assembly plants attempt to mitigate some of the adverse effects of higher variety by building labor slack into the system, thereby introducing an additional fixed cost of product variety.

5. Simulation Results

To triangulate the results from our field research and data analyses, we designed a simulation model to represent the essential features of the General Motors Wilmington plant, scaled down in size for computational tractability. We used the model to confirm some important observations from our field research and data analyses. Figure 5.1 provides a schematic representation of the simulated assembly line. Cars are assumed to move along the line at a constant speed. The line's cycle time, which without loss of generality is assumed to be one minute, is the time interval between two successive cars passing any fixed point along the line.

Each worker is assigned a workspace along the line and performs a particular operation. A worker can only perform an operation on a given car while the car is within his assigned workspace. For example, referring to Figure 5.1, worker j-1 is assigned to work within the interval between *a* and *b*. He can begin work on car i-1 as soon as it passes point *a* (for simplicity, we assume cars have zero length so that the entire car passes a given point in a single instant). If he has not completed his operation by the time the car reaches point *b*, then the line stops until he completes his operation.

We can represent this situation with the following notation:

m = the number of work stations.

n = the number of cars to be assembled in the simulation run.

t_{ij} = the time to complete the operation at work station j on car i. In general, this is a random variable that is determined using Monte Carlo techniques.

$dwell_j$ = length of the time interval during which a car is available (or dwells) in work station j.

We assume that the starting points of the workspaces along the line are spaced evenly at one minute intervals so that car i becomes available at work station j at time i + j - 2. Operation j can begin on car i as soon after this time as the worker has completed operation j on car i-1. If the operation is not completed by time i + j-2+$dwell_j$, then the line stops until the operation is completed.

In our primary method for generating t_{ij}, the work stations were segmented into two categories depending on whether the workstation installed an option or not. We assume there are k possible options. Option j is installed at a single workstation i_j, requires OT_j minutes and occurs on a given car with probability p_j. We set $OT_j = 1/p_j$ and $dwell_j = OT_j$, so that the average operation time is 1 and $dwell_j$ is long enough for the operation on a car with an option to be completed without stopping the line. Note, however, that if two or more options occur in succession, the worker would get behind and the line would stop.

In a particular simulation, t_{ij} for option-related work stations are set by Monte Carlo generation of the option configuration of each car. For all of the remaining work stations and cars, we set $dwell_j = t_{ij} = 1$ for all i. These work stations would not cause line stoppage.

After t_{ij} were generated for a sample of n cars, we determined an assembly sequence for the n cars that was intended to evenly space the occurrence of options at work stations. To be more precise, let n_j denote the number of times an option occurs at work station j in a sample of n cars (in expectation $n_j = n\,p_j$, but in a particular sample of cars n_j could differ from this value due to randomness). In an ideal sequence, a car requiring an option should arrive at work station j every n/n_j cycles. For example, if n = 15 and five cars require an option at work station 1, then the start times for these cars should be 0, 3, 6, 9 and 12. If this sequencing can be achieved for all option-related work stations and the number of cars with options does not exceed $p_j\,n$, then all operations can be performed without line stoppage.

Our sequencing rule attempts to create a sequence that comes as close as possible to this ideal case by choosing a next car in the sequence from the unsequenced cars that maximizes a sequence score that equals the sum of the times by which the start time of each option on that car would exceed the start time of an ideal sequence. Note that the score for a car can be negative if choosing the car would result in options re-occurring in too short an interval. Most auto plants use sequencing algorithms similar to this, with the algorithms applied each day to the set of cars scheduled for assembly that day. To simulate the daily sequencing that occurs in the real world, we assumed that the n cars in a simulation correspond to a fixed number of daily batches and applied the sequencing algorithm to each daily batch of cars. In all of our runs, m = 50, n = 2000 and the number of days equaled 10. Hence, the sequencing algorithm was applied to successive daily batches of 200 cars in the 2000 car simulated sample. These cars can be processed in 2050 cycles. We ignored the first 50 and last 50 cycles since they correspond to situations in which the line is not completely loaded.

In all of our simulations, all p_j were set to a common value p and the work stations affected by options were $[m_j/k]$, j = 1, ..., k. Forty different values for k and p were simulated using the following values: (1) p = .5 and k = 1, ..., 10; (2) k = 5 and p = .25, .3, .35, ..., .7; (3) k = 1..., 10 and p chosen so that the standard deviation in total labor content (σ_{time}) was equal to 3; and (4) k = 1, ..., 10 and p chosen so that the standard deviation of the number of options (σ_{count}) was equal to .5. It is easy to show that $\sigma_{time} = \sqrt{k(1-p)/p}$ and $\sigma_{count} = \sqrt{k\, p\, (1-p)}$. For each of these cases we tabulated the total time that the line was stopped and used this to compute the percentage increase in labor content due to line stoppage. To compute the percentage increase in direct labor, we note that total labor with no stoppage over the simulated time is 50 x 1950 and the time lost due to stoppage is 50 times the total time that the line is stopped.

For each of these cases, we also experimented with buffering those operations affected by options with additional capacity. We ignored the integrality constraint on capacity imposed by workers and assumed that capacity could be expanded continuously with a proportionate reduction in operation times. Note that increasing capacity at all option-related work stations by a certain percentage increases the amount of labor assigned to the work station by the same percentage, but red uces the additional labor required due to line stoppage. We used Fibinacci search to find the optimal buffering level in each case simulated and computed the resulting percentage increase in total labor content due both to buffering and line stoppage.

Our field observations indicated that random contingencies are another source of variability in plants due to factors such as defective parts or work on preceding operations that is performed incorrectly. Because these random contingencies can also cause line stoppage, we sought to compare the amount of line stoppage caused by option variability to an equivalent amount of purely random variability. To do this, we made a run for each simulated case in which all t_{ij} were chosen uniformly from the interval $[1 - \Delta, 1 + \Delta]$. Note that the standard deviation in labor content is given by $\sigma_{time} = \sqrt{m}\ \Delta^3 /3$. We used this result to choose a Δ that would equalize σ_{time} in the random case with σ_{time} in the corresponding option case.

The results from the 40 simulation runs are provided in Table 5.1. The first set of runs held the probability of an option constant at 0.50, but varied the number of options from 1 to 10. Standard deviations in both work content time and the number of options increase as the number of available options goes up. Consistent with the empirical tests, this increased variability is accompanied by greater direct labor content due to increased line stoppage. However, buffering the line with additional labor capacity reduced the productivity losses due to line stoppage, providing theoretical support for the buffering observed in the Wilmington plant.

The second set of runs held the number of options constant at 5 but varied the probability that an option would be included on a car from 0.25 to 0.70. As the probability of an option being included increased, the standard deviation in work time decreased. The standard deviation in option counts, however, first increased and then fell as option penetration reached 0.60 or greater. Line stoppages in both the buffered and unbuffered simulations followed a pattern similar to the pattern in option counts, first increasing and then decreasing, with the peak line stoppage percentages occurring when option penetration ranged from approximately 0.45 to 0.60. These results suggest that assembly plants are better off when options are installed on only a small fraction of cars or on a large percentage of car, supporting the industry practice of installing many "options" as standard equipment on most cars. Once again, the buffered line experienced significantly fewer line stoppages than the unbuffered line, a result consistent with the empirical evidence.

In the third set of tests, both the number of options and the probability that an option is installed are varied so that the standard deviation in work content remains equal to 3.00. Although the variability in work content remains the same, the standard deviation in option counts increases with the number of options, as does the amount of line stoppage in both the buffered and unbuffered simulations. Our field research made it clear why this happens. If only one option is offered, it would be easy to achieve a sequence of perfectly spaced options. As the number of options grow, however, a plant is prevented from doing this because the ideal sequence for one work station may not be the ideal sequence for another. Consequently, the probability that a worker will encounter a sequence of cars that cannot be completed in the allowable cycle time increases, causing line stoppages or rework to increase.

In the fourth set of tests, the number of options and the probability that an option is installed are varied so that the standard deviation of option count remains constant at 1. The fact that the percent increase in labor content with buffering is essentially constant at 2-3% for these runs further establishes that the standard deviation of option counts is the principal driver of lost direct labor productivity due to options.

In all of the simulations, random variability caused a significantly greater percentage increase in labor content than option variability. These results suggest that the impact of option variability can be partially mitigated by sequencing cars to space options. In contrast, random variability cannot be anticipated, indicating that auto manufacturers should be even more zealous in their attack on random variability than they are in trying to reduce option variability. It is not clear that all auto manufacturers are following this logic.

To better understand the role of option "bundling" on direct labor productivity, we repeated all the experiments assuming that options were bundled. That is, a given car either had all options or no options. With bundling, it is easier to obtain a sequence that perfectly spaces options since there are only two categories of cars, those with no options or those with all options. As a result, we would expect the percentage increase in labor content to be reduced by bundling. This is confirmed in Table 5.2, especially in the buffered case.

6. Conclusion

Prior research on the relationship between product variety and manufacturing performance has provided conflicting results. In contrast to previous studies, we employ three sources of data to develop and test hypotheses regarding the impact of variety on automobile assembly. The field evidence, data analyses, and simulation models allow us to triangulate the findings and provide deeper insight into the various means through which variety affects productivity.

Our results provide a number of implications for future research. First, the distinction between fixed and variable costs of variety is an important one that has received relatively little attention in the academic literature. If plants have invested in fixed resources that minimize the adverse effects of product variety, studies examining the statistical association between variety and productivity can find little impact from high variety, even though significant fixed costs have been incurred due to higher product variety.

The evidence also indicates that the manufacturing *variability* introduced by higher product variety has a greater impact on productivity than the *number* of product variations. If a large number of options are installed on *all* cars, production planning and material handling are straightforward, and the production task facing the line worker does not vary by vehicle. In contrast, greater variability increases the complexity of production planning and material handling activities and raises the probability of defects and downtime. Consequently, simple proxy variables for variety such as the number of parts or number of products may not allow researchers to capture the impact of variety on manufacturing performance.

Although research on assembly line balancing has a long history in the management science literature, little research has examined line balancing issues in mixed-model assembly operations such as an automobile assembly line. Our evidence suggests that line balancing provides only a partial solution to the product variety problem in these settings. Although labor buffers and kitting operations (which make product variety transparent to the assembly worker by sequencing parts off line) can help to alleviate variety-related contingencies, they introduce additional fixed costs into the system. Additional research on line balancing in mixed-model assembly operations can help to minimize the variety-related losses that currently plague automobile manufacturers.

Finally, although variety-related variability is found to reduce productivity, our field observations and simulation results suggest that random variability is even more disruptive to factory operations. Although the impact of option variability can be mitigated to a certain extent by line sequencing and option bundling, reducing random variability requires organizational changes that extend beyond the technical solutions used to minimize the effects of option variability.

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TABLE 4.3
The association between changes in option variability and changes in direct labor hours per car;
time series data covering 151 production days

(t-statistics in parentheses)

	Body Shop Hours/car	Paint Hours/car	Trim Hours/car	Chassis Hours/car	Final assembly Hours/car
Constant	0.03 (0.05)	0.01 (0.33)	0.07 (1.40)	-0.01 (-0.14)	0.02 (0.84)
Average Options/Car	-8.46 (-0.95)	-0.05 (-0.14)	-0.03 (-0.35)	0.02 (0.04)	1.28 (0.46)
Option Variability	-34.09*** (-3.22)	0.08 (0.02)	-0.08 (-0.53)	0.56 (0.66)	0.82 (1.12)
Body Shop Downtime	578.3** (2.52)	130.7*** (19.66)	283.6*** (24.81)	214.9*** (8.82)	28.8*** (9.46)
Startup Indicator	-2.77 (-0.44)	-0.79 (-0.29)	-1.17** (-2.52)	-0.49 (-0.51)	-0.02 (-0.12)
Adj. R^2	.11	.84	.89	.52	.48
F-statistic	3.82***	117.9***	181.4***	25.5***	25.6***
Durbin-Watson	2.00	1.81	2.00	1.75	1.86

***, **, and * = Statistically significant at the 1%, 5%, and 10% levels (two-tailed test), respectively.

TABLE 4.4

The association between changes in option variability and changes in production downtime and final assembly hours per car;

time series data covering 151 production days

(t-statistics in parentheses)

	Total Downtime (% of Production Time)	Final Assembly Hours/Car
Constant	0.003* (1.97)	-0.006 (-0.04)
Body Shop Downtime	0.642*** (18.95)	29.12*** (17.21)
Startup Indicator	0.0001 (0.11)	0.043 (0.58)
Option Variability--Body Shop[a]	-0.003 (-1.36)	-0.180 (-0.91)
Option Variability--Paint	-0.001 (-0.71)	-0.027 (-0.13)
Option Variability--Trim	0.004*** (2.93)	0.031* (1.80)
Option Variability--Chassis	0.022** (2.33)	0.19*** (2.61)
Option Variability--Final Assembly	0.006 (1.57)	0.437 (1.57)
Adj. R^2	.93	.87
F-statistic	170.0***	88.01***
Durbin-Watson	1.97	1.76

***, **, and * = Statistically significant at the 1%, 5%, and 10% levels (two-tailed test), respectively.

a. Variability measures pertain to options impacting that particular process step.

Table 5.1 Simulation Results

2000 cars, 50 work stations, 10 days Mean time = 50 minutes.
Standard Deviation - Time is in minutes

Number of Options	Prob of an option	Standard Time	Deviations Count	Percent Increase in Labor Content Unbuffered	Buffered	Random*
1	0.50	1.00	0.50	2	2	25
2	0.50	1.41	0.71	3	3	35
3	0.50	1.73	0.87	7	5	43
4	0.50	2.00	1.00	13	8	49
5	0.50	2.24	1.12	18	10	55
6	0.50	2.45	1.22	23	12	60
7	0.50	2.65	1.32	27	14	65
8	0.50	2.83	1.41	29	16	69
9	0.50	3.00	1.50	31	18	74
10	0.50	3.16	1.58	34	20	77
5	0.25	3.87	0.97	14	7	95
5	0.30	3.42	1.02	15	8	84
5	0.35	3.05	1.07	17	7	75
5	0.40	2.74	1.10	19	9	67
5	0.45	2.47	1.11	17	10	61
5	0.50	2.24	1.12	18	10	55
5	0.55	2.02	1.11	23	8	50
5	0.60	1.83	1.10	23	7	45
5	0.65	1.64	1.07	22	5	40
5	0.70	1.46	1.02	20	4	36
1	0.10	3.00	0.30	6	1	74
2	0.18	3.00	0.55	8	2	74
3	0.25	3.00	0.75	8	3	74
4	0.31	3.00	0.92	12	6	74
5	0.36	3.00	1.07	19	8	74
6	0.40	3.00	1.20	21	13	74
7	0.44	3.00	1.31	23	16	74
8	0.47	3.00	1.41	25	17	74
9	0.50	3.00	1.50	31	18	74
10	0.53	3.00	1.58	33	18	73

* Random chooses all process times uniformly in the interval 1-delta, 1+delta, where delta chosen to give same standard deviation as the unbuffered and buffered cases.

Table 5.2 Simulation Results with Bundled Options

2000 cars, 50 work stations, 10 days Mean time = 50 minutes.
Standard Deviation - Time is in minutes

Number of Options	Prob of an option	Standard Time	Deviation Count	Percent Increase in Labor Content	
				Unbuffered	Buffered
1	0.50	1.00	0.50	1	1
2	0.50	2.00	1.00	2	2
3	0.50	3.00	1.50	1	1
4	0.50	4.00	2.00	2	2
5	0.50	5.00	2.50	2	2
6	0.50	6.00	3.00	3	3
7	0.50	7.00	3.50	7	7
8	0.50	8.00	4.00	7	7
9	0.50	9.00	4.50	8	8
10	0.50	10.00	5.00	2	2
5	0.25	8.66	0.30	4	3
5	0.30	7.64	0.77	7	1
5	0.35	6.81	1.30	11	4
5	0.40	6.12	1.85	11	3
5	0.45	5.53	2.40	8	1
5	0.50	5.00	2.94	2	2
5	0.55	4.52	3.47	18	8
5	0.60	4.08	3.99	15	7
5	0.65	3.67	4.50	18	5
5	0.70	3.27	4.99	18	4
1	0.10	3.00	2.17	9	1
2	0.18	4.24	2.29	5	0
3	0.25	5.20	2.38	4	2
4	0.31	6.00	2.45	6	1
5	0.36	6.71	2.49	11	4
6	0.40	7.35	2.50	12	3
7	0.44	7.94	2.49	10	2
8	0.47	8.49	2.45	6	1
9	0.50	9.00	2.38	8	8
10	0.53	9.49	2.29	20	6