The cost of flexibility

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Abstract

Purpose – In the automobile industry, the variety of vehicles produced continues to increase. At the same time, historically firms have incurred a sizeable productivity penalty for producing more variety in their plants. The purpose of this paper is to answer the question: what actions have firms taken to control this productivity penalty and what were the costs?

Design/methodology/approach – Estimate a number of statistical models of the effect of variety on productivity for a sample that includes almost all assembly plants in North America from 1994 to 2004.

Findings – Evidence is found for fixed costs associated with activities that are complementary to producing variety and for a trade-off between scale economies and flexibility.

Research limitations/implications – Provides evidence that while flexibility has an advantage to cope with increasing variety, there are non-negligible costs as well.

Originality/value – A first systematic evaluation on the scale-scope trade-off and a quantification of the gains from production flexibility in the automotive industry.

Keywords Automotive industry, Productivity rate, North America, Statistical analysis

Paper type Research paper

1. Introduction

In the automobile industry the number of different models offered for sale has increased dramatically over time, especially in the last 20 years. As in many mature industries, firms differentiate their products from their competitors' to temper price competition and the accompanying erosion of profit margins. While this makes perfect sense from a revenue perspective, there are cost implications. In particular, we show that producing a wider range of platforms, models, body styles, or chassis configurations is associated with a substantial productivity penalty.

Before we turn to the steps that firms have taken to tackle this problem, we first illustrate both phenomena – the increase in model variety and the accompanying productivity penalty. The number of models for sale in North America, in Table I, shows a clear upward trend, growing from 185 in 1974 to 320 in 2004. The number of offerings in the US more than doubles over the 30 year period. This growth is concentrated in light trucks, which includes currently popular crossover vehicles. The number of models – unique nameplates – is not the entire story, as the growth in number of variations for both cars and trucks illustrates. Each model is built in a variety of body styles and different chassis configurations.

This increase in the number of vehicles for sale was not driven by imports: the number of models produced in North America has grown even more rapidly (by 83 percent versus 73 percent for models sold). Finally, the number of assembly plants in North America has remained relatively constant, even declining in the last decade, forcing firms to produce several models side by side in their plants.

The increase in average product variety assembled within each plant has slowed down productivity growth. Table II contains the coefficient estimates for a least squares regression with hours-per-vehicle (hpv), the usual measure of (inverse) labor productivity in the automobile industry, as dependent variable and different measures of variety, a time trend, and the interaction of both variables as explanatory variables[1].The negative time trend illustrates that productivity is increasing over time. The average labor requirement per vehicle declines by approximately 57 min per year[2]. At the same time, the positive coefficients on the first line indicate that labor requirements increase with the number of varieties produced by plant. For example, assembling an extra platform increases the average labor requirement per vehicle by two-and-a-half hours. The corresponding increases for an extra model, body style, or chassis configuration are 1.61, 0.56, and 0.44 h, respectively. For less profound differences between varieties, a different body style is not as

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Table I The number of models sold and/or produced in North America has increased substantially over time

	Sample period			
	1974	1984	1994	2004
Models for sale in North America	185	228	273	320
Models for sale in United States	133	195	238	282
Car models	96	140	164	167
Car variations	–	–	468[a]	503
Light truck models	37	55	74	115
Light truck variations	–	–	558[a]	1,805
Models produced in North America	90	125	139	165
Assembly plants in North America	68	76	68	64

Note: [a]1996 – not available
Source: Ward's Communications (1975-2005)

profound a change as a different platform, the productivity penalties decline as well, but they always remain positive and highly significant.

Crucially, the penalty for variety has decreased over time. The coefficient on the interaction between variety and time, on the third line in Table II, is always estimated negatively and relatively large. For our preferred measure of variety – the sum of chassis configurations and body styles – the productivity penalty associated with producing one extra variety falls from 38 min in 1994 to a mere 5 min in 2004[3]. Given that the average variety rises from 4.35 to 5.64 over the same time period, the labor input savings are clearly non-negligible.

Flexible assembly plants are often presented as the miracle solution to produce greater variety, but they come at a price. We will show that there is no free lunch. Firms can adopt activities that diminish the productivity penalty associated with variety, but these tend to lower baseline productivity. The incremental cost of variety is reduced, but it comes at the expense of higher input requirements when few varieties are produced. As a result, adopting these activities will not be optimal for all plants.

While the flexible technology that characterizes the production process at some modern plants has drastically reduced the productivity penalty associated with variety, we also show that the technology tends to have lower scale economies. Whether full flexibility is the optimal strategy for any given plant depends crucially on its current and future product mix and scale of operation. The continuous decline of the average model run suggests that increased flexibility is likely to become desirable for ever more North American automobile assembly plants.

The remainder of the paper is organized as follows. Section 2 introduces a simple model of production that provides a framework for thinking about variety in production. The empirical specification is provided in Section 3. Section 4 describes the data and Section 5 discusses the results. Conclusions are in Section 6.

2. Model

To fix ideas consider the following simple model. Total labor hours required to assemble a vehicle can be divided into the direct labor input on each vehicle and externalities on other types of vehicles produced in the same plant, which can be positive or negative:

$$\text{Hours} = \sum_{i=1}^{N} \left[\alpha Q_i + \sum_{j \neq i}^{N} \beta Q_j \right], \qquad (1)$$

i and j index the N varieties assembled in the plant. The marginal labor requirement for each extra vehicle is α hours and additionally it increases (or decreases) the labor requirements on all vehicles of a different type by β. Equation (1) can be rewritten as:

$$\frac{\text{Hours}}{Q} = \underbrace{(\alpha - \beta)}_{\alpha'} + \beta \text{ Variety}, \qquad (2)$$

using "Variety" for N and $Q = \sum_i^N Q_i$ for total output[4].

2.1 Complementarities

One way to reduce the productivity penalty associated with greater variety is to adopt complementary activities. Complementarities between activities are characterized by a

Table II Productivity penalty associated with production of greater variety

	Dependent variable: hpv				
	Platforms (1)	Models (2)	Chassis configurations (3)	Body styles (4)	Configurations + styles (5)
Variety	2.522*** (0.564)	1.612*** (0.299)	0.564*** (0.135)	0.437*** (0.158)	0.353*** (0.082)
Time	−0.961*** (0.136)	−0.946*** (0.133)	−0.932*** (0.135)	−0.966*** (0.136)	−0.945*** (0.135)
Variety × time	−0.239 (0.147)	−0.334*** (0.077)	−0.067 (0.043)	−0.091* (0.048)	−0.055** (0.024)
Observations	860	860	860	860	860
R^2	0.539	0.552	0.541	0.532	0.540
Productivity penalty (hpv) associated with producing one more variety in					
1994	3 h 43′	3 h 17′	54′	54′	38′
2004	1 h 20′	−3′	14′	−1′	5′

Notes: Estimation by least squares on the entire sample of North American assembly plants. Controls include the logarithm of production capacity (scale), dummies for the vehicle segment of a plant's output, country (Canada or Mexico) and foreign ownership dummies, and a dummy for the pre-1998 period as the dependent variable was defined somewhat differently. Standard errors in parentheses; *significant at the 10 percent level; **5 percent; ***1 percent joint impact on some return function, productivity in our case[5]. Two examples of such activities are "flexibility" measured as the ability to produce more than one platform on a single assembly line, and "insourcing" measured as the fraction of activities that are conducted in-house. We conjecture that each of these activities is complementary to the production of greater variety, meaning they will reduce the spillovers (β) of one model-type on each other type. It is likely that these activities will also have a direct effect on labor input requirements. We will estimate a linear parametrization of the model:

$$\alpha' = \alpha_0 + \alpha_F \text{ Flexibility} + \alpha_I \text{ Insourcing} + \alpha_{FI} \text{ (Flex.} \times \text{Insourcing)} + \alpha_S \text{ Scale} + \alpha_T \text{ Time} \quad (3)$$

$$\beta = \beta_N + \beta_F \text{ Flexibility} + \beta_I \text{ Insouring}$$

Substituting these equation (2) generates our first estimating equation. The dependent variable, hpv, is the inverse of labor productivity. The α coefficients capture direct effects and the β coefficients capture the impact of variety on productivity. The main prediction we want to test is that both activities are complementary to variety, i.e. they decrease spillovers ($\beta_F < 0$ and $\beta_I < 0$).

Flexibility makes the entire production process more complicated and is expected, *ceteris paribus*, to lead to higher direct labor requirements and a positive linear (α_F) coefficient. The benefit will be to lower labor requirements of other varieties produced in the same plant – captured by a negative β_F coefficient. Duplicating assembly lines when radically different vehicles are produced would lead to corresponding increases in labor requirements. In contrast, facilitating production on the same assembly line will raise labor input less than proportional to variety.

Doing more tasks inhouse, greater insourcing, will straightforwardly increase direct labor requirements ($\alpha_I > 0$). If this generates useful expertise it can reduce the spillovers on other types of vehicles, possibly even reducing their labor input requirements. One mechanism could be the existence of task and vehicle type specific fixed costs to organize and maintain outsourcing relationships (e.g. managing deliveries), while fixed costs to perform an inhouse task are to a lesser extent model specific (e.g. training workers).

It is also possible that flexibility and insourcing are complementary themselves (if $\alpha_{FI} < 0$). We include the interaction effect, but do not have a prior on the sign of the coefficient. Through the α' function, we control explicitly for scale economies (expected to be positive, i.e. $\alpha_S < 0$), and productivity growth (also expected to be positive, $\alpha_T < 0$). Other factors, such as the type of vehicle produced, ownership, and location are controlled for as well. We do not have a strong prior on the direction of those effects and include them in the constant term (α_0).

2.2 Flexible technology

An alternative approach to consider the impact of flexibility is to assume that there exist two different technologies that differ in their evolution of productivity and other aspects influencing productivity. The theoretical model in Milgrom and Roberts (1990) illustrates how complementarities will lead to joint adoption of all activities[6]. Intermediate systems that mix and match activities will be unstable. Production technologies are likely to differ in terms of scale economies, productivity growth, and the productivity penalty associated with variety (and possibly other dimensions as well). For each of its plant, a firm will adopt the most appropriate technology given its product mix and scale of operation. In terms of the model of production in equation (1), two sets of α and β coefficients exist:

$$\alpha^\tau = \alpha_S^\tau \text{ Scale} + \alpha_T^\tau \text{ Time}$$
$$\tau \in \{\text{Flexible Technology}, \text{Mass Technology}\} \quad (4)$$
$$\beta^\tau = \beta^\tau$$

Our prior is that the older "Mass" technology has the advantage of higher scale economies ($|\alpha_S^M| > |\alpha_S^F|$), because of greater standardization of tasks and increased automation. The drawback is that producing greater variety within a plant leads to a larger increase in labor input requirements ($|\beta^M| > |\beta^F|$)[7]. No particular difference in productivity growth is assumed, but if the most rapid technological evolution accrues to the newer technology, see for example, Christensen (1997), we would find that ($|\alpha_T^M| < |\alpha_T^F|$).

3. Empirical specification

The two models we propose to estimate – as described by equations (3) and (4) – pose distinct empirical challenges. If adoption of the potentially complementary activities is endogenous, as is likely, we have to take that into account in the estimation. We follow the approach advocated in Athey and Stern (2003) and use activity-specific instruments. Rather than estimating the adoption decisions directly, we follow the framework proposed in Van Biesebroeck (2006) and estimate the productivity equation directly, using interactions of the instruments as additional instruments (see footnote[5] for a justification).

We are able to reject the null hypothesis that all three activities – variety, flexibility, and insourcing – are exogenous and, hence, estimation by least squares will give biased results. Results in Van Biesebroeck (2006) point most strongly to either adoption or flexibility as endogenous, while the p-value for the test of endogeneity of variety is higher than 0.99. Three sets of results will be reported. The least squares results are the benchmark, where coefficients should be strictly interpreted as shifting the mean of the conditional expectation, without any causal inference. Co-movement of the activities might be, at least to some extent, driven by unobserved heterogeneity and/or omitted variables.

Using a GMM estimator, we instrument for flexibility using the size of the plant (a proxy for the ability to duplicate assembly lines) and type of shift relief (a proxy for management-workforce labor relations). Both of these variables are plausibly predetermined from the perspective of the much shorter term decision on flexibility[8]. For insourcing we use the distance from the North American and the country specific industry centers as instruments. Plants located far away from the center of automotive activities will find it, *ceteris paribus*, harder to outsource tasks. These distances are unlikely to be correlated with the unobserved plant level productivity that we are concerned about. To control more generally for unobserved heterogeneity we also estimate the GMM model including plant fixed effects.

To estimate the second model, which assumes all plantyear observations in the sample use one of two possible technologies, we have to somehow classify observations by technology. The simplest approach is to assume that a singe observable variable is a perfect proxy for technology. For example, all plants built before 1982 – the year the first transplant started producing – might operate according to the old technology, with newer plants using the flexible technology. Ownership could be another proxy for technology and we also estimate the model using different productivity equations for foreign and domestically-owned plants.

An alternative approach is to integrate out the unobserved technology state. With 11 years of data and two possible states, there are 2^{11} or 2,048 possible technology paths for each plant. To put some structure on the evolution of technology, we assume that the flexible technology is an absorbing state. Once a plant has chosen to adopt the newer, flexible technology, it will not switch back to the older, mass technology[9]. This allows us to parameterize the transition probability from the old to the new technology as a function of observable variables and estimate those parameters together with the parameters in the two productivity equations (4).

When a plant is first observed in the sample, there is a probability z_{i0} that it produces with the "Mass" technology (M) and with probability $1 - z_{i0}$ it already uses the "Flexible" technology (F). The transition probabilities in subsequent years are shown in Table III.

Variables in Z determine the probability a firm finds it more beneficial to produce with the flexible technology in plant i, rather than sticking with the mass technology[10]. The initial and adoption probabilities are modeled as a function of a number of exogenous variables: the foreign ownership and built pre-1982 dummies, and calendar time. In addition, we include the instruments used for flexibility and insourcing from the first model as pre-determined variables that influence these probabilities as well.

With this additional structure, there are only 12 possible technology paths. A plant can enter the sample producing with the flexible technology, in which case it will never change its production technology. This happens with probability $(1 - z_{i0})$. Alternatively, it enters with the mass technology and adopts the flexible technology after the first year, after which the technology is fixed again. The probability for this sequence of events is $z_{i0}(1 - p_{i1})$. If the switchover happens in the second year, the plants production history is weighted by $z_{i0}\ p_{i1}(1 - p_{i2})$, and so forth. For each of the 12 possible technology paths we write out the probability of observing the hpv variable as a function of the explanatory variables using the relevant equation (4) with a normally distributed error term appended. Estimation can then proceed with maximum likelihood as in Van Biesebroeck (2003).

Table III

		Technology at time $t+1$	
		M	F
Technology	M	$p_{it} = 1/(1+\exp(Z_{it}\gamma))$	$1 - p_{it} = \exp(Z_{it}\gamma)/(1+\exp(Z_{it}\gamma))$
At time t	F	0	1

4. Data

The plantlevel information we already used for the preliminary results in Table II comes from *The Harbour Report North America*, published in 1980, 1981, 1989, and annually from 1994 onwards. All statistics are constructed using a uniform methodology from information supplied by the firms, supplemented with plant visits by representatives of Harbour Consulting. Firms voluntarily agreed to provide information to benefit from the productivity benchmarking exercise Harbour performs.

To guarantee coverage of the universe of plants in North America and a uniform definition of variables over time, the sample period is limited to 1994-2004. Almost all car and light truck assembly plants in the USA, Canada, and Mexico are sampled, but some observations are dropped because of missing values. We estimate that the final sample covers 95 percent of the plants in the industry, accounting for an even larger share of output.

The performance measure used as dependent variable is the standard measure of (the inverse of) labor productivity in the industry: hpv. For this to be an useful productivity measure, one has to assume that other inputs are constant across time and plants or vary proportionally to output. While obviously a strong assumption, it is not entirely implausible for this industry. Similar to the situation in Ichniowski *et al.* (1997), firms share the same technology (a moving assembly line), the production process follows the same steps (welding together stamped panels, painting the body, and assembling all components to the vehicle) and final products are made up of the same set of components. The scope for substitution between different inputs is clearly limited[11].

Crucial explanatory variables in the analysis are the number of varieties produced, flexibility in production, the extent of outsourcing, and scale of operation. Our preferred measure of model proliferation is the sum of the number of body styles and chassis configurations produced in the plant. This measure captures actual physical differences between vehicles, which is not guaranteed with the other measures (models or platforms). The results in Table II suggest that results are likely to be similar for the other measures. For flexibility we use the number of platforms produced per production line as this ability is likely to facilitate increasing variety in the plant's output[12]. Our measure of outsourcing is the fraction of tasks, from a list of 29, that a plant performs in-house[13]. Finally, the scale of operation is measured by the logarithm of production capacity, calculated as potential output over the year using the usual shift pattern and line-rate.

We use instruments for flexibility and outsourcing as these are choice variables of the firm and potentially correlated with unobserved plant-level productivity differences. Instruments for flexibility are the size of the plant in square footage (area) and whether shift relief is "mass" or "tag"[14]. The extent of outsourcing is instrumented by the distance from each plant to the midpoint of the automotive industry in North America and to the industry's mid-point within the plant's country. Distances are calculated from the plants' longitudes and latitudes and change slightly over time as the centers shift[15].

Control variables included in all regressions include location dummies (the USA, Canada, or Mexico); ownership dummies (the USA or foreign-owned)[16]; a year trend and a dummy for the pre-1998 period to control for the change in measurement of the dependent variable; segment dummies ((sub-)compact cars, mid/full-size cars, sport/ speciality cars, luxury cars, SUVs, pickup trucks, minivans, and full-size vans)[17]. A discussion of the relevance of the productivity measure and summary statistics for all variables are in Table AI in the Appendix.

5. Results

Results on complementarities, using the equation (3) and three different estimators, are in Table IV. While the point estimates vary considerably across the different columns, all signs are invariant to the estimation method. The coefficients on (uninteracted) variety, flexibility, and insourcing are all positive and, with only a single exception, significantly different from zero. Increasing either of these activities increases the baseline labor input requirement per vehicle. We find large and positive scale economies (a negative coefficient on scale) when we compare across plants, in columns (1) and (2), but the effect is much smaller if we compare within plants over time, in column (3). Productivity growth, on the other hand, is almost as large when we only use variation over time as including variation across plants.

Most importantly, the interactions between variety and flexibility and between variety and insourcing are negative, as expected. It indicates that the two activities lower the incremental labor input requirement associated with the production of increased variety. Producing greater variety is less costly in terms of lost productivity if flexibility and insourcing are increased at the same time. Moreover, the interaction of flexibility and insourcing is negative as well, suggesting that the direct productivity penalty associated with either activity, as captured by the uninteracted coefficients, is reduced if they are adopted jointly. This joint effect makes it hard to attribute effects to either activity and the point estimates tend to vary a lot across the different columns.

The least squares results, in column (1), still allow for unobserved heterogeneity or an omitted variable as potential explanation for the joint effect of different variables. For example, a plant-specific shock might lower the productivity penalty associated with variety, while at the same time lowering the adoption cost for flexibility. The GMM results point more strongly towards a causal interpretation, attributing the diminished productivity penalty for variety to the increase of the two complementary activities. The addition of firm fixed effects, in column (3), increases the standard deviations on most coefficient estimates – now coefficients are identified solely from variation over time. Still, all signs are as before and the coefficients on (variety × flexibility) and (variety × insourcing) remain significant and strongly negative.

The nonlinear effects make it difficult to interpret the magnitudes of the coefficient estimates directly. In Figure 1, we use the coefficient estimates from column (1) to predict how quickly hpv grows with variety for different levels of flexibility and insourcing[18]. The black line illustrates that, evaluated at the average levels of flexibility and insourcing, a one standard deviation increase in variety (by 4.1), say from the sample average of 5.5-9.6, raises the average hpv by slightly more than 2 h, from 30.5 to 32.6. If a plant were more flexible the increase would be reduced, as evidenced by the negative interaction coefficient on (variety × flexibility). Evaluating the impact of the same increase in variety for a plant at the 90th percentile level of flexibility (producing one and a third platform per line instead of one), the hpv increase would be only 1.8 h. Similarly, a plant that was at the 90th percentile of insourcing (doing three quarters of all tasks inhouse) would only see an increase of 0.9 h. Finally, a plant that was both very flexible and insourced a lot would see hpv increase by only 38 min (the white line in Figure 1).

Moreover, adopting flexibility or insourcing is accompanied by a fixed cost, evidenced by the positive coefficient on the uninteracted effects in Table IV and visible as an upward shift in the curves in Figure 1. The intercept for a flexible plant (dashed line) is 0.62 higher and for an insourcing plant it is 1.91 higher. It is intuitive that insourcing, the activity with the highest return in terms of lowering the productivity penalty for variety, also has the highest fixed cost. Adopting both activities together will shift the intercept up by 2.47 instead of 2.53 (the sum of the two previous shifts) as the interaction effect of the two activities is negative[19]. As a result, for all plants producing more than six varieties, the 70th percentile level of variety in the sample, adopting both activities is optimal, i.e. the white line lies below the other three.

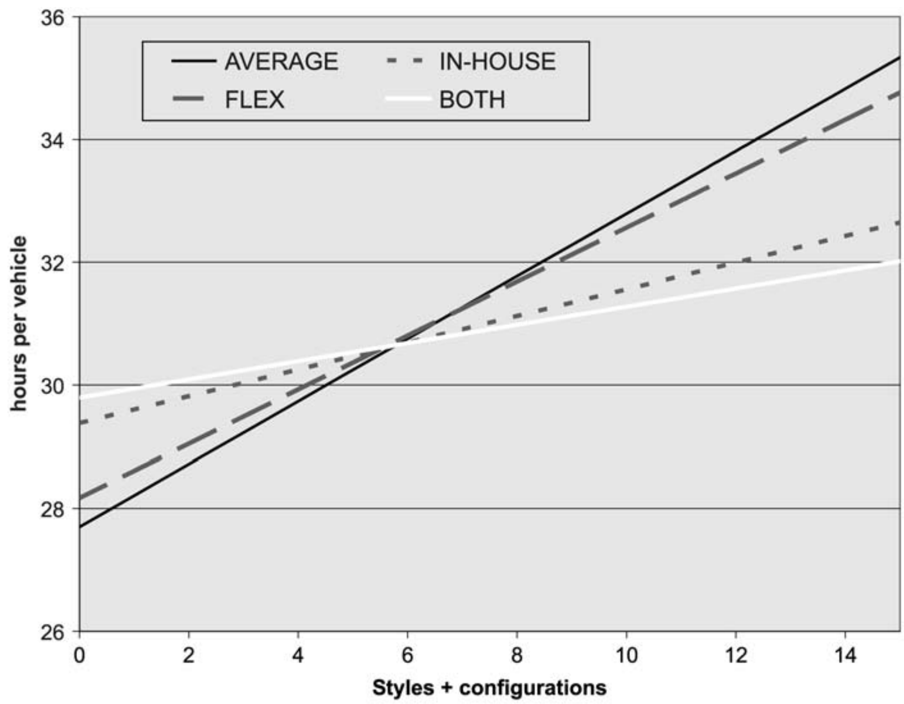
An alternative way of analyzing how the penalty associated with variety evolves is to conjecture that there are two technologies available. A crucial difference is likely to be the

Table IV Productivity regressions under different exogeneity assumptions

	Dependent variable: hpv		
Estimation method	**OLS (1)**	**GMM (2)**	**GMM with plant FE (3)**
Variety	1.618*** (0.436)	4.915*** (1.625)	7.476*** (1.742)
Insourcing	9.455*** (2.860)	13.203*** (3.955)	20.477** (8.757)
Flexibility	2.600 (2.012)	22.413*** (6.755)	10.711** (4.714)
Scale	−11.880*** (0.723)	−10.488*** (1.326)	−0.748 (2.251)
Time	−0.922*** (0.134)	−1.159*** (0.223)	−0.898*** (0.179)
Variety × insourcing	−1.622*** (0.488)	−0.638** (0.280)	−7.044** (2.523)
Variety × flexibility	−0.292 (0.273)	−3.845*** (1.544)	−2.984*** (1.111)
Flexibility × insourcing	−1.139*** (0.334)	−21.321*** (7.329)	−9.300 (8.272)
Observations	860	860	860
R^2	0.554	0.141	0.619

Notes: Variety, flexibility and insourcing are measured as continuous variables. In columns (2) and (3), instruments for insourcing are the distance to the industry center for North America and within the plant's country and for flexibility they are the plant area and a dummy for tag shift relief. Interactions of instruments are included as well. The same set of controls as in Table II are included; *significant at the 10 percent; **5 percent; ***1 percent

Figure 1 Predicted hpv (using OLS estimates)



Note: The black line (AVERAGE) evaluates hours-per-vehicle at the average for all variables, including flexibility (1.09) and insourcing (0.36), using the OLS estimates in equations (2) and (3). The dashed line (IN-HOUSE) uses the 90th percentile value for the insourcing index (0.76) and the average for all other variables. The grey line (FLEX) uses the 90th percentile value for the flexibility index (1.33) and the while line (BOTH) uses the 90th percentile values for both insourcing and flexibility

tradeoff between realizing economies of scale and getting penalized for producing variety: the scale-scope trade-off[20]. The main empirical challenge is to determine which plants in the sample produce with either technology.

Results in the first two columns of Table V deterministically separate all observations (plant-years) in two groups based on ownership. Coefficients in column (1) characterize the productivity of domestically-owned plants and those in column (2) indicate the difference for foreign-owned or joint venture plants from this baseline. Domestic plants realize very large-scale economies, improve productivity very quickly over time, but incur a productivity penalty of 22 min per extra variety – body style or chassis configuration. Foreign plants realize lower scale economies and lower productivity growth. The difference coefficients are both positive and significant. Moreover, the two groups of plants are indistinguishable in the productivity penalty for variety. The only advantage for foreign plants is a much lower constant term – baseline hpv. The average hpv for foreign plants in 1994 was 24.24 versus 36.66 for domestic plants. The difference declines to 22.01 versus 25.55 by the end of the sample period.

Slightly more intuitive results are obtained if we separate plants in two groups based on their original construction year: before or after 1982. The NUMMI plant is the only foreign-owned plant that is "old," while 12 Big Three plants, including several in Mexico, are "new." The differences in scale economies and productivity growth become less pronounced, while new plants now reveal a minor scope advantage (a lower productivity penalty for variety), but the difference is not significantly different from zero.

The results in the last two columns of Table V are for the model that integrates out the unobserved technology state, allowing plants to adopt the flexible technology at some point over the sample period. Now the results indicate clearly that the mass technology (the one that firms can switch out of) has higher scale economies, but this comes at the expense of a greater productivity penalty for variety. Doubling capacity at a mass plant lowers hpv by 11 h 13′ but only by 3 h 26′ in a flexible plant. In contrast, each extra variety added to the production mix in a mass plant raises the average hpv by 52′ but only by 23′ in a flexible plant. The latter is not even significantly different from zero. In addition, the model now predicts a lower baseline hpv for mass plants, but more rapid productivity growth in flexible plants. All of these differences now correspond to our priors.

As a result, the model proliferation that we demonstrated in Figure 1 makes the flexible technology preferable for ever more plants – consistent with current trends in the industry. We estimate the initial probability of operating with the flexible technology (in 1994 or the first year a plant is observed in the sample) and the probability of switching over to the flexible technology as a function of observable characteristics. These are reported at the bottom of Table V. Few coefficients are significant, but we can report that foreign owned plants are more likely to start out flexible, while plants built after 1982 are more likely to adopt the flexible technology.

In Figure 2, we use these estimates to predict the probability a plant is flexible. The dots indicate for each

Table V Productivity regressions with two distinct technologies

	Dependent variable: hpv					
	Separate two samples		Separate two samples		Integrate out unobserved technology state	
Estimation method	**Domestically owned**	**Foreign owned**	**Old plants**	**New plants**	**Mass technology**	**Flexibile technology**
Technology	**Baseline**	**Difference**	**Baseline**	**Difference**	**Baseline**	**Difference**
Coefficients	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
Variety	0.373^{***} (0.080)	0.077 (0.395)	0.349^{***} (0.088)	−0.072 (0.165)	0.865^{**} (0.349)	-0.468^{*} (0.280)
Scale	-15.001^{***} (0.854)	8.495^{***} (1.679)	-14.726^{***} (0.966)	5.231^{***} (1.403)	-11.216^{***} (2.006)	7.778^{***} (2.115)
Time	-1.151^{***} (0.091)	1.016^{***} (0.219)	-1.084^{***} (0.099)	0.516^{***} (0.187)	-1.174^{***} (0.302)	−1.070 (0.930)
Constant	$2,515.1^{***}$ (182.4)	$-2,140.2^{***}$ (434.4)	$2,380.0^{***}$ (197.9)	$-1,097.2^{***}$ (372.7)	$2,430.2^{***}$ (557.3)	2,137.4 (1,789.9)
Parameters governing technology state					Initial probabilty	Transition probability
Time					-0.321^{*} (0.175)	-0.073^{*} (0.044)
Foreign-owned					-2.079^{**} (0.505)	1.522 (1.789)
Built after 1982					0.070 (0.106)	-2.503^{*} (1.487)
Distance from center					−0.004 (0.008)	0.002 (0.012)
Tag relief					-0.410^{*} (0.190)	0.122 (0.087)
Constant					4.626 (4.610)	2.003^{***} (0.566)
Observations	147	713		239	621	860
R^2	0.568		0.552			

Notes: The first two columns are estimated on two separate samples, separating plants by ownership (joint ventures are considered foreign-owned). Columns (3) and (4) similarly separate plants in two samples by built-year: prior to or after 1982. In the last two columns, the unobserved technology state is integrated out (see details in the text). The flexible technololgy is the absorbing state. The same set of controls as in Table II are included in each specification and these coefficients are forced to be equal for the two technologies. The second column in each comparison indicates the difference between the second and the first technology. Coefficients in the bottom panel are for the *Z* variables in the initial probability for flexible technology, column (5), and for the transition probability, in column (6); *significant at the 10 percent; **5 percent; ***1 percent observation the estimated probability it is operating with the flexible technology (the size of the marker is proportional to the number of plants at each point). The line indicates the average probability in each year. By the end of the period, in 2004, the average probability for the flexible technology has risen from 0.08 to almost 0.75, but there are still plants for which the probability is estimated below one half. It makes intuitive sense that the flexible technology is not optimal for all plants, but the rise in variety, see Table I, makes it desirable for more and more plants over time. For a large part of the sample period, especially pronounced between 1996 and 2002, plants fall in two distinct groups: those with a high and others with a low probability of operating with the flexible technology with few plants in between. At the same time, there are a few plants that are predicted to have operated with the flexible technology throughout.

6. Conclusions

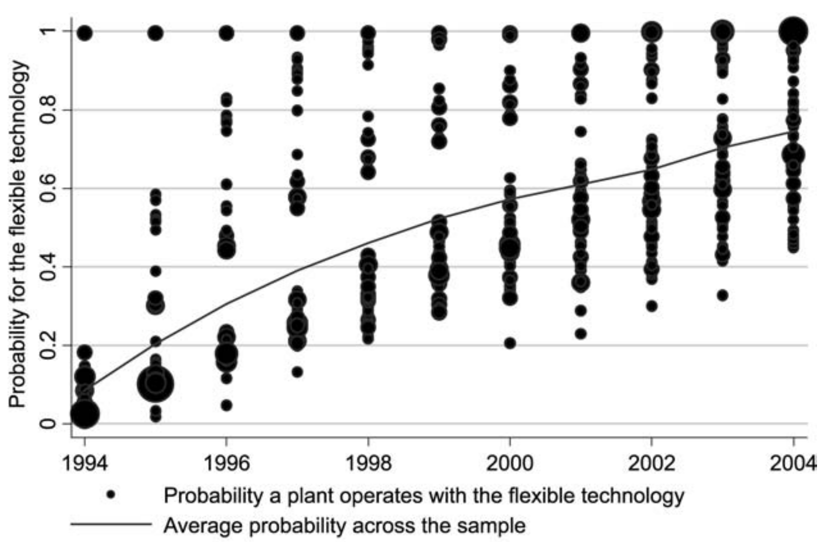
We have shown that in the recent past automobile assembly plants have faced a productivity penalty for producing greater variety. By 2004 this penalty had been virtually eliminated. Adoption of activities complementary to producing variety – insourcing and flexibility – have been shown to reduce the penalty at the margin. The drawback is that they increase the baseline number of hours required to assemble a vehicle. According to the admittedly restrictive specification we estimate, plants that produce more than six body styles or chassis configurations would be better off raising their level of insourcing and flexibility to a level attained by the 75th percentile in the sample in 2004 (90th percentiles over the entire sample period).

We also estimated an alternative model that allows for two different technologies to coexist. Instead of affecting the marginal productivity penalty for variety, technologies are now conjectured to differ discretely. Plants operating with the older mass technology can choose to adopt the newer flexible technology at each point in time. We find evidence that the mass technology has a higher baseline productivity and higher scale economies. The flexible technology, on the other hand, experiences faster productivity growth and incurs a statistically significant lower productivity penalty if variety is added to the plant. Given this characterization, it is no surprise that the flexible technology is becoming more popular over time, reaching an average of almost 0.75 by the end of the sample period.

Notes

1 Detailed information on the data follows in section 4. Controls are included for the scale of operation, the type of vehicle produced, location and ownership dummies, and a pre-1998 dummy to account for a slightly different definition of the dependent variable.
2 Across specifications, the time coefficient varies between 0.932 and 0.966, which corresponds to average annual reductions in hpv between 56 and 58 min.
3 The 1994 statistic is calculated as $0.353 - 0.055 \times (-5) = 0.628$ hours and $0.353 - 0.055 \times (+5) = 0.078$ for 2004.
4 We assume that the direct effects (α) dominate the indirect effects (β) such that $\text{sign}((\partial(\alpha - \beta))/\partial X) = \text{sign}(\partial\alpha/\partial X)$ for any variable X.
5 The return function we use is similar as in Arora and Gambardella (1990) or Ichniowski *et al.* (1997). While these authors estimate the adoption decisions that the first order conditions imply, we estimate the objective function directly. Theoretical work, see Jovanovic and Stolyarov (2000), suggests that with learning and fixed costs joint adoption is no prerequisite nor sufficient for complementarities. Moreover, our activities evolve continuously over time, making the "time of adoption" hard to define.
6 A "technology" is merely a shorthand name for a group of activities. The Milgrom and Roberts (1990) paper defines "modern manufacturing" – as opposed to "mass production" – as the joint adoption of flexible machine tools, production in small batches, shorter product cycles, reduction in work-in-progress and finished goods

Figure 2 Evolution of the predicted probability for flexible technology in the sample



Note: The size of the marker is proportional to the number of plants inventories, just-in-time deliveries of components, electronic data communications, and made-to-order.

7 As before we still expect to find for either technology that scale economies are positive, $\alpha_S^{\tau} < 0$, and that there is a positive productivity penalty associated with variety, $\beta^{\tau} > 0$.

8 The instruments pass the usual over identification test, see Van Biesebroeck (2006).

9 See Van Biesebroeck (2003) for a more elaborate justification.

10 The starting probabilities for either technology are a similar function of a set of observable variables: $z_{i0} = 1/(1 + \exp(Z_{i0}\delta))$.

11 Capital input is likely to be relatively similar across plants and materials and intermediate inputs vary proportionally to output. All specifications include vehicle segment dummies and some of the results include a full set of plant fixed effects, absorbing all differences that are constant over time. The data appendix elaborates on robustness checks for the appropriateness of the hpv measure.

12 A production line is defined as the average number of body and assembly lines per plant.

13 A complete list of the tasks can be found in the *Harbour Report*.

14 Under mass relief, all workers in the plant change shifts at the same time, while the assembly line is stopped for 15 min. Under tag relief, individual workers relieve the worker on the previous shift they are replacing.

15 For US plants the exact location is taken from the US Environment Protection Agency's web site www.epa.gov/air/opar/auto/. For Canadian and Mexican plants, we use the center of the town where plants are located.

16 Joint venture plants are treated as foreign-owned.

17 In the rare cases where vehicles from more than one segment are produced, the dummies are weighted by production shares.

18 The figure looks similar using the estimates from other columns, but the larger coefficients (in absolute value) on variety and the interaction effects lead to steeper curves. The slopes change in the same direction if insourcing and/or flexibility are increased.

19 This effect for joint adoption is more pronounced for the GMM results as the interaction coefficient on (flexibility × insourcing) is estimated much larger.

20 Chandler (1990) discusses this tradeoff at the firm level in a historical context.

21 Prior to 1998 a slightly different productivity measure was calculated: workers-per-vehicle (*wpv*). This measure ignored daily fluctuations in production and converted employment to fulltime equivalent workers. Because both measures are available in 1998 and 1999, all *wpv* statistics can be converted to hpv using a conversion factor that varies by owner (firm) and country of location (of the plant). In all regressions we include a pre-1998 dummy. We have also performed the analysis excluding all pre-1998 observations and found virtually identical results.

22 Retooling is defined as a capacity change of more than 10 percent or the introduction of a vehicle from a different segment. The short duration of the panel makes this variable censored for almost 50 percent of plants.

23 For example, in 2003 the only discrepancy is that Toyota is estimated to require on average 2 percent less hpv than Honda, while it makes lower profits per vehicle (compare tables on pages 30 and 150 in the 2003 *Harbour Report*).

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Appendix

The Harbour data has one disadvantage relative to using data collected by the US Bureau of the Census, as in Van Biesebroeck (2003): the absence of capital stock information. As a result we have to use hpv, the standard measure of (the inverse of) labor productivity in the industry, as dependent variable[21]. The main advantage is the ability to include Canadian and Mexican plants and to use rich information on the types of products assembled in each plant. Relative to the data set constructed from plant surveys by the International Motor Vehicle Program, see MacDuffie (1995), the benefit of The *Harbour Report* information is the complete coverage of the North American industry and the time dimension in the panel.

The absence of information on investments in fixed capital or capital stocks makes it impossible to calculate multifactor productivity. However, at the final assembly stage in this industry

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capital intensity tends to be relatively similar across plants. Infrastructure investments are usually provided by local or state jurisdictions in order to "level the playing field" in the bidding war to attract FDI, see Appel Molot (2005). Using plant level census data (which contains capital stock information), Van Biesebroeck (2003) estimates different capital coefficients for "lean" or "mass" technology plants. The estimated capital elasticities are very similar, 0.136 and 0.106, and not significantly different even at the 10 percent level, although differences in the operation of the plants or productivity growth were large.

In each regression, we include country dummies. Only if the capital labor substitution varies by plant within the same country will the labor productivity measure be misleading. Wages are especially low in Mexico and substitution of labor for capital is most likely to occur there. In a robustness check we omitted the Mexican observations and found very similar coefficient estimates of all variables of interest.

Another robustness check includes plant-fixed effects to absorb capital stock differences between plants and results are again extremely similar. Finally, to capture technological innovations embodied in the capital stock we also experimented with the inclusion of information on the year the assembly plant was last retooled, but that variable was always insignificant[22].

For comparability reasons, the *Harbour Report* presents the hpv comparisons by segment. We will include segment dummies in each regression to account for the complexity of the vehicle produced, e.g. plants assembling luxury cars have on average a higher hpv than plants assembling compact cars.

While the physical productivity comparison embodied in the hpv statistics is of obvious interest to identify complementarities in production, it would be useful to have an idea of the wider importance of this performance measure. Unfortunately, no other plant-level information is publicly available. One possibility would be to adjust hpv for the value of the vehicle produced. Unfortunately, a crucial aspect of the analysis is that models are sold in different configurations or styles. We do not observe the breakdown of production by variety, while prices vary a lot (up to 100 percent). At the firmlevel, the *Harbour Report* calculates each year a comparison of North American pretax profit per vehicle. In most years the ranking of firms is identical to the hpv ranking, as proof of its importance[23] (Table AI).

Table AI Summary statistics (1994-2004)

	Mean	Standard deviation	Min	Max
Dependent variable				
Hpv	30.13	11.41	15.69	108.51
Activities				
Number of chassis configurations	2.67	2.46	0.75	23.10
Number of body styles	2.84	2.21	1.00	16.00
Number of (configurations + styles)	5.51	4.08	1.75	39.10
Number of models	2.11	1.04	1.00	6.00
Number of platforms	1.23	0.54	1.00	5.00
Log capacity	12.15	0.44	9.30	13.07
Flexibility index	1.09	0.34	0.50	3.33
In-sourcing index (inverse of outsourcing)	0.36	0.17	0.00	0.92
Instruments				
Distance (from NA center, miles)	517.57	406.20	61.99	1,915.07
Distance (from country center, miles)	309.75	314.71	17.45	1,918.01
Area (million square feet)	2.45	0.97	0.22	5.50
Mass relief	0.41	0.49	0.00	1.00
Controls				
Pre-1998 dummy	0.28	0.45	0.00	1.00
Canadian plant	0.20	0.39	0.00	1.00
Mexican plant	0.09	0.29	0.00	1.00
Foreign-owned plant	0.17	0.37	0.00	1.00
Number of observations	860			
Number of unique plants	92			

Source: *The Harbour Report* (1995-2006)

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