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**AN EMPIRICAL STUDY OF
MANUFACTURING FLEXIBILITY IN
PRINTED-CIRCUIT BOARD ASSEMBLY**

**Fernando F. Suarez, Michael A. Cusumano,
and Charles F. Fine**

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Abstract

This paper begins with a literature review and framework for analyzing different types of flexibility in manufacturing and how plants can implement each type in different ways. Next, we examine some of the propositions in the framework using data from 31 printed circuit-board plants in Europe, Japan, and the United States. Our findings include the following: (1) More automation is associated empirically with less flexibility, as found in other studies. (2) Non-technology factors, such as high involvement of workers in problem-solving activities, close relationships with suppliers, and flexible wage schemes, are associated with greater mix, volume, and new-product flexibility. (3) Component reusability is significantly correlated with mix and new-product flexibility. (4) Achieving high mix or new-product flexibility does not seem to involve a cost or quality penalty. (5) Mix and new-product flexibility are mutually reinforcing and tend to be supported by similar factors. (6) Mix flexibility may reduce volume fluctuations, which may theoretically reduce the need for volume flexibility. Based on our analysis and findings, we then suggest several new strategic insights related to the management of flexibility and some potentially fruitful areas for further theoretical and empirical research.

I. Introduction¹

In contrast to literature in the 1970s that applauded the benefits of the "focused factory" and concentrations on relatively narrow product lines (Skinner, 1974), much has been written in recent years about "flexible factories" and "flexible manufacturing systems" able to produce a variety of quality products at low cost. Yet the lack of standard and precise definitions has limited the use of the concept of flexibility in strategic and competitive analysis. Few researchers have measured flexibility or related constructs; and those that have attempted this all too often have measured flexibility quite simplistically. Because of these problems with empirical studies of flexibility, many basic questions that managers need to address remain unanswered: How many different types of flexibility are there? Under which conditions is a firm likely to benefit from a given type of flexibility? How many different ways are there to implement each of the different kinds of flexibility? What are the relationships or tradeoffs among the different flexibility types with regard to productivity, and quality?

This article addresses these and other questions related to manufacturing flexibility by using empirical data collected from printed circuit board (PCB) assemblers in the United States, Japan, and Europe during 1991-1992. We attempt to make several contributions to the literature. First, on the theoretical side, Section II proposes an integrative framework to analyze manufacturing flexibility from a strategic perspective, building on previous research as well as factory visits done as part of this study. Section III describes the industry and the sample, and discusses the generalizability of this type of study. Section IV deals with the measurement of different types of flexibility, following a multi-dimensional approach. Section V discusses the implementation of flexibility, tests the importance of each possible source of flexibility, and examines their significance in light of the industry under study. Section VI deals with the evaluation of flexibility and explores two types of relationships: potential trade-offs between efficiency and quality among the different flexibility types; and the notion of relatedness, rather than trade-offs, among different flexibility types at least in how they have been implemented in this industry.

There are six major empirical findings highlighted in our study: (1) As found in other studies, more automated plants tend to be less flexible, despite the programmable nature of most equipment used in this industry. (2) Non-technology factors, such as high involvement of workers in problem-solving activities, close relationships with suppliers, and flexible wage schemes, appear to increase mix, volume, and new-product flexibility. (3) Component reusability appears to raise both mix and new-product flexibility. (4) Achieving high mix or new-product flexibility does not seem to involve a cost or quality penalty. (5) Mix and new-product flexibility are mutually reinforcing and tend to be supported by similar factors. (6) Mix flexibility may reduce volume fluctuations, which may theoretically reduce the need for volume flexibility.

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II. Literature Review and Theoretical Framework

The objective of this section is to highlight very briefly the main work that has been done on manufacturing flexibility over the last decade in order to serve as a background for the framework used in this paper. Extensive literature reviews on the topic can be found elsewhere (e.g. Sethi and Sethi, 1990). Here we summarize our earlier literature review (Suarez, Cusumano, and Fine 1991), which divided the existing literature into two main streams: analytical models and empirical studies.

The analytical models of flexibility have come almost exclusively from the fields of operations research and operations management. As Fine (1989) described, there have been four main concerns in the modelling literature: (1) flexibility and life cycle theory; (2) flexibility as a hedge against uncertainty; (3) interactions between flexibility and inventory; and (4) flexibility as an strategic variable that influences competitors' actions (mostly game-theoretical models). Analytical models of flexibility often have a common setting: two types of production technologies are available to a firm, one dedicated and one flexible (such as a flexible manufacturing system or FMS). An FMS can produce two (or more) products very efficiently, but it is assumed to cost more than a dedicated line. Different assumptions about demand (random, seasonal, or S-shaped, for instance), timing, and reversibility of the investment are made in order to suit the particular problem being explored by the author. Then the conditions under which one technology is preferable to the other are determined.

We divide the empirical literature into four groups. The first group has been concerned with developing *taxonomies of flexibility*. Many different types of flexibility have been proposed, but the use of different names to refer to the same type of flexibility has added some unnecessary confusion. Some of the important contributions in this sub-category are Gerwin (1987), Buzacott (1982), Mandelbaum (1978), Browne (1984), Slack (1983, 1988), Kumar and Kumar (1987), and Zelanovic (1982). The second group deals with the relationship between *flexibility and performance*, and includes a few studies that present data to support their claims. Examples are Jaikumar (1986), Tombak (1988), Tombak and de Meyer (1988), and Fiegenbaum and Karnani (1991). The third group deals with *historical and economic analyses of flexibility*, and tends to view flexibility as an attribute of importance for the competitiveness of a firm, industry, or country. Scholars in this group come usually from the social sciences, and include Piore and Sabel (1984), Harrigan (1984), Storper and Christopherson (1986), Adler (1985), Womack, Jones, and Roos (1990), and Cusumano (1992). A fourth group consists of literature reviews or strategic frameworks that analyze flexibility, including Sethi and Sethi (1990) and Suarez, Cusumano, and Fine (1991). The latter authors, as well as Hyun and Ahn (1990) and Gerwin (1991), have also proposed strategic frameworks that try to show, based on existing literature, how firms can use or implement flexibility in different competitive situations.

A review of the literature on manufacturing flexibility indicates that there are four basic types, which we have incorporated into our framework:

- Mix Flexibility
- Volume Flexibility
- New-Product Flexibility
- Delivery-Time Flexibility

In turn, the literature indicates that there are at least four factors which affect the need for flexibility:

- Product Strategy of the Firm
- Behavior of Relevant Competitors
- Product-Demand Characteristics
- Stage in the Life Cycle of the Industry

The literature also suggests six factors that affect the implementation of flexibility:

- Production Technology
- Production Management Techniques
- Relationships with Subcontractors, Suppliers, and Distributors
- Human Resources (training and skills of the work force, employment security and compensation policies)
- Product Design
- Accounting and Information Systems

This simple framework suggests several propositions that should be measurable and testable empirically: (1) Different types of flexibility exist and are important to firms in different competitive situations. (2) There are different ways of achieving each type of flexibility. And (3) different approaches to flexibility may have different costs and tradeoffs with respect to productivity, quality, and other dimensions of firm or plant performance.

For example, mix flexibility would probably be important when a plant or firm offers a full-line of products, producing for many different segments of the market. It will probably be less important for a plant or firm focused on a specific market segment. As we will see below, PCB assembly plants vary substantially in terms of the number of final applications they produce for; plants producing for multiple market segments will need greater mix flexibility than their focused counterparts. Mix flexibility can also be obtained in several ways. For instance, labor-intensive plants may rely on skilled workers who can perform a variety of tasks effectively in order to achieve mix flexibility. Capital-intensive plants would probably increase their mix flexibility through programmable production equipment and sophisticated information systems. Finally, skilled workers or sophisticated equipment -- or any other way of achieving mix flexibility -- may imply an additional cost to the plant. Alternatively, greater levels of mix flexibility may affect the quality level of a plant, as workers and machines are less "specialized" in a few particular tasks. The consideration of the trade-offs of flexibility in section VI of this paper will shed light on these issues.

The framework proposed here is larger than the scope of our data. In this paper, we concentrate on the measurement, implementation, and evaluation of three flexibility types: mix, volume, and new-product flexibility.

III. The Industry and the Sample

The process of assembling printed circuit boards consists primarily of placing a variety of different components on a wired raw board through the use of either machines or hand assembly. Components vary greatly in terms of shape, technological sophistication, and process requirements; and they range from simple resistors to

complex microprocessors and chips with a high number of gates (transistorized switches). Most plants use two basic technologies to place components on a board: through-hole placement and surface-mount technology (SMT). In through-hole insertion, axial- and radial-leaded components are soldered to the surface of the board with lead protrusions. Surface-mount, a newer technology which mounts components on the surface without lead protrusions (thus using only one side of the board, leaving the opposite face "free"), is attracting most of the new PCB assembly investment and promises to become the industry standard. Surface mount technology does not require holes on the board and allows for the possibility of placing components on both faces of the board. Two-way component mounting plus multi-layered board design are increasingly important given the constant search for denser boards to be used in ever smaller electronic products.

The printed-circuit board assembly industry can be divided into two major groups of players: captive plants, producing for downstream plants or divisions of the same firm; and independent plants or contract manufacturers, which sell their assembly services to different firms. Our study considers only captive plants.

The printed circuit board assembly industry exhibits several characteristics that make a study of this type difficult. First, most of the plants in the industry are highly automated, which implies that the human-related factors of flexibility implementation will tend to be less relevant here than in a more labor-intensive industry. Second, the production process is quite standardized. Most plants purchase their PCB assembly equipment from a few major vendors, so there is less variation in the production process in this industry than in other assembly industries. Third, PCB assembly is an intermediate industry which supplies assembled boards to be used in final applications. This implies that customers are manufacturing firms, rather than the actual end users. Finally, as we said above, our study only considers captive plants. This has two implications for us. On the one hand, plants in our sample tend to be more insulated from market pressures than plants competing in the open market. Thus, they may be slower and less responsive in implementing different flexibility types than plants in the open market might be. On the other hand, the fact that all our plants belong to large corporations makes it difficult to control for corporate-wide resources and policies that might be influencing a plant's behavior.

Because of the above factors, our results should only be considered as a reference point when looking for similar patterns in other industries. As we will see, several of the hypotheses derived from the general framework still hold in the PCB assembly industry (and new ones emerge from the data analysis), but others tend to be weakly supported or not supported at all with the data. Still, we think the framework proposed here may be applied fruitfully in many manufacturing contexts. The strengths of the relationships in each case will probably vary, but the framework should still help structure the study of flexibility.

Despite its difficulties as a case study for this topic, we selected the PCB industry for several reasons. First, we were aware from various research contacts that PCB manufacturers were already studying flexibility issues and thus had data on hand to answer questions in which we were interested. Second, managers appeared to be less concerned with data confidentiality compared to manufacturers of final products, which we also considered for this study. The ability and willingness to provide data were essential for an empirical study like this one. Third, the fact that printed circuit boards are used in a variety of applications allowed us to draw a sample

from numerous companies with potentially diverse plants.

Our sample is composed of 31 plants belonging to 14 electronics firms based in the United States, Europe, and Japan. We did not select these firms randomly; with one exception, all are large electronics manufacturers who are members of programs at the Massachusetts Institute of Technology (the Leaders for Manufacturing Program, the International Center for Research on the Management of Technology, and the Industrial Liaison Program). Companies provided data in three basic forms: questionnaires, plant visits by the authors, and in-person or telephone interviews. We started by visiting plants to discuss our study proposal and the type of metrics we were interested in collecting. Then, a 20-page questionnaire was pilot-tested, improved, and then administered to all plants in the sample in mid-1991. The questionnaire asked detailed questions about the production process, equipment, products, and organizational characteristics of each plant. We followed up the questionnaire with plant visits and telephone interviews in order to gain a better understanding of the responses. Overall, we visited 16 plants and conducted phone interviews with all of them. Next, a follow-up questionnaire was sent in early 1992 to the respondents, clarifying some of their answers to the first questionnaire and asking them new questions based on our better understanding of the industry. We also sent a short third questionnaire in March 1992 and conducted additional telephone interviews, primarily to clarify issues related to our previously collected data. The breakdown of our sample in terms of geographical region and final application of the boards is given in Table 1.

IV. Flexibility Measurement

In this section, we discuss separately the measurement of mix, volume, and new-product flexibility.

Mix Flexibility: Mix Flexibility has received a great deal of attention in the, probably because it is very intuitive and has direct market implications. Mix flexibility has almost always been measured by the number of products that a system produces at any point in time; thus, it is easy to equate mix flexibility to the breadth of the product line. For instance, Kekre and Srinivasan (1990) have discussed the relationship between a broader product line and market success. They found that a broader product line tends to be associated with larger market share and profitability, and that it does not seem to be associated with higher costs.

We believe, however, that in most cases mix flexibility cannot be measured by the simple count of the different products produced by the system. Rather, one must also measure the heterogeneity of the product set. A simple example will clarify our point. Think of two plants, A and B, each producing two products of the same kind, say computers. Plant A produces A_1 and A_2 and plant B produces B_1 and B_2 . Both plants will be equally mix flexible according to the "breadth of the product line" definition. However, product A_1 is significantly different from product A_2 (say, A_1 is a traditional personal computer and A_2 is a laptop), whereas B_1 and B_2 are both "traditional personal computers" (the difference being only speed and RAM characteristics). A more rigorous analysis should determine that plant A has greater mix flexibility than plant B.

Assembled printed circuit boards present the same sort of problems that

computers or other products do. Boards are produced for different final applications and they vary in size (and size has effects on the complexity of the assembly process), density (number of components per area), testing requirements, and other characteristics. Simply counting the number of different boards produced by a plant will not tell us all we want to know in order to calculate metrics for mix flexibility. Therefore, in this study, we use the following four variables to measure mix flexibility. Note that the variables capture physical, technological, and market differences:

- (1) the number of different board models assembled by each plant (BRDMOD90).
- (2) the number of different board sizes used during assembly by each plant (NBBRDSIZ)
- (3) the range of board density handled by each plant (in components per square centimeter, standardized with respect to the mean--RNDENSIT).
- (4) the number of product categories in which the boards produced by a plant are used (PRDCATEG).

Different product categories are found in every final application. Examples of product categories are VCRs, televisions, and stereos in the consumer electronics industry, and laptop computers, personal computers, and minicomputers or mainframes in the computer industry.

Table 2 gives summary statistics of the variables measuring mix flexibility. Note that the sample includes plants with widely different degrees of mix flexibility. For instance, the least mix-flexible plant produces only two boards, each of a different size, for the same product category, and with a density range equivalent to less than ten percent of the average density of the two boards that it assembles (this plant shows the minimum value for each of the four variables considered). In contrast, another plant in the sample assembles 2002 different board models in 300 different board sizes, with a density range of almost three times the average density of the plant.

While it is informative to consider each of the four measures of mix flexibility because it reminds us of the multi-dimensional nature of the construct, ideally one would like an aggregate measure. The ideal aggregate measure should include the information from each of the component variables. In this study we rely on an established multivariate statistical technique, principal components analysis (PCA), to create an aggregate measure of mix flexibility. The technique of principal components analysis creates "n" linear combinations (called principal components) from "n" original variables, with coefficients equal to the eigenvectors of the correlation matrix (see Gnanadeskikan 1977 and Morrison 1976 for discussions of this technique).

Principal components calculated in this way have several interesting properties, one of which is very important for our purposes: the first principal component "explains" the largest fraction of the original variables' variance explained by any other component. This property allows us to use the first component as an aggregate measure of the original variables, provided that the first component captures a significantly high portion of the original variance. The percentage of variance captured by a composite is known as the composite's eigenvalue. As a rule of thumb, most researchers keep in their analysis those components that achieve eigenvalues greater than one. This is sensible given the way principal components are calculated.

The technique implicitly standardizes the variables that are being combined, so that each variable "contributes" with one unit of variance to the analysis. The idea of keeping composites with eigenvalues greater than one is that the new composite should at least explain as much variance as any original variable. The negative side of principal components analysis is that we lose some interpretability in the analysis, as the new aggregate measure does not have a clear meaning in the physical world. (However, no combination of different variables would have an easy interpretation either.)

We take the natural logarithm of each variable to proceed with the principal components analysis. This turns out to be an appropriate transformation not only because it helps us overcome possible scale problems, but also because plots of the raw variables revealed some non-linearity in the data. Indeed, the transformed variables show stronger correlation coefficients than the raw variables. Table 3 below presents the results of the principal components analysis. The table shows that the first component captures 73 percent of the variance explained by the four variables in the analysis. Note that the eigenvalue for the first component is much higher than the eigenvalue of the other components. Moreover, only the first component's eigenvalue is greater than one. Thus, the first component is a reasonable proxy for an aggregate measure of the four variables, i.e. it is a good proxy for mix flexibility. The weights of each variable in the first component, indicated by the variable's eigenvector, are very similar. Thus, for interpretation purposes, it is appropriate to think of the first component as a sort of "average" of the four variables. Note though that this "average" has the useful property of being the linear combination that maximizes the variance explained by the original variables.

Volume Flexibility: Stigler (1939) is an early reference for a discussion about volume flexibility. His reasoning, as re-interpreted and formalized by Marschak and Nelson (1962), is that a firm's volume flexibility is reflected in the shape of its average total cost function. A flat average cost function gives a firm more flexibility, as it can depart from the optimal output without much cost penalty. Recall from basic economic theory that a firm in competition maximizes profits by producing at the lowest point of its average cost curve, where marginal revenue equals marginal cost. The traditional mathematical formulation of this problem involves a linear total cost function with fixed cost. An estimate of volume flexibility can then be obtained by the inverse of the second derivative of the total cost function (see Marschak and Nelson 1962 for details).

During the last decade, several authors in the manufacturing, operations management, and strategy literatures have referred to the potential importance of volume flexibility. However, few articles have attempted to measure volume flexibility or to study the ways in which it is implemented by a plant or firm. A few authors have suggested ways in which flexibility could be measured. For instance, Falkner (1986) suggests looking at the stability of costs as production fluctuates. Gerwin (1987) suggests measuring it by the ratio of average volume changes to the production capacity limit, over a specific period of time. Sethi and Sethi (1990), expanding on Browne's (1984) proposition, suggest that volume flexibility could be measured by the range of volumes in which the firm can run profitably. Fiegenbaum and Karnani (1991) actually measure volume flexibility as the standard deviation of annual sales. They focus on studying the relationship between volume flexibility, firm size, and profitability using aggregate data from the COMPUSTAT database. With a very parsimonious model that includes firm size as the only explanatory variable, they find

that smaller firms tend to show greater fluctuations in sales or, in their terms, greater volume flexibility.

In this article we stress the important distinction between volume fluctuations and volume flexibility. Some researchers such as Fiegenbaum and Karnani seem to have used both concepts interchangeably. Following the lead of Stigler, we stress that only volume flexibility is a "desirable" attribute of a production system. Volume (or sales) volatility, as most managers would agree, is an undesirable attribute even in those organizations considered to be flexible and responsive to market demands. For instance, in describing the emergence of the "Toyota production system," Monden (1983) and Cusumano (1985) point out that maintaining level production over time is a central tenet of the Toyota approach. As we will see later in this paper, volume fluctuations may be incompatible with other types of flexibility, which provides an additional reason for the undesirability of fluctuations.

We actually measured both volume fluctuations and volume flexibility. Our volume fluctuation measure is based on data about the ratio of highest monthly board production to lowest monthly board production for three years. From these data a reasonable measure of volume fluctuation can be obtained for each plant as follows:

$$\text{Production Volume Fluctuation} = \left(\frac{(R_1)^2 + (R_2)^2 + (R_3)^2}{3} \right)^{1/2}$$

where R_1 is the ratio of highest monthly board production to lowest monthly board production for year 1. This measure and its component ratios for our sample are shown in Table 4 below. (Note that, obviously, a simple variance measure for 36-month production would have been more desirable. Unfortunately, the monthly data were not available to make such a computation.)

We now define volume flexibility as the ability to vary production with no detrimental effect on efficiency and quality. In some cases, larger volume fluctuations may be associated with higher costs or lower quality levels. The work of Stigler (1939) and Marschak and Nelson (1962), mentioned earlier, provide theoretical support for this perspective. Thus, the flexibility implied by larger volume fluctuations may have to be weighed against these potential negative effects on cost and quality. Our reasoning is as follows: A plant that is able to shrink and expand its production volume widely and still keep its cost low and quality level high, is more volume-flexible than a firm that presents the same volume fluctuation but has much higher costs and lower quality. Consider the following measure of volume flexibility, where production volume fluctuation is calculated as above:

$$\text{Volume Flexibility} = \text{Log} \left(\frac{\text{Production Volume Fluctuation}}{\text{Cost per placement} + \text{Fraction of boards with some repair}} \right)$$

Note that this measure increases in production volume fluctuation, decreases in cost per placement, and decreases in the fraction of boards that undergo some repair (a quality measure); higher scores indicate more volume flexibility. Other

things being equal, the measure penalizes plants with higher cost or lower quality levels. Table 5 presents summary statistics of volume flexibility in our sample. Note that the correlation between this measure and volume fluctuations is only 0.22, which is consistent with our argument that volume fluctuations alone should not be used as a proxy for volume flexibility.

New-Product Flexibility: The ability to create new products quickly is an attribute that has become extremely important in many industries today. As technology advances rapidly and customers become more sophisticated, rapid product introduction can give firms a real competitive advantage. The subject of product development and introduction has been studied extensively by several researchers in the past decade (Clark and Fujimoto 1991; Imai, Nonaka, and Takeuchi 1985) and has also received attention from the marketing and general management literature (e.g. Urban and Hauser 1980, Abegglen and Stalk 1985). Most of the studies on product development have been done at the project level, in contrast to our analysis at the plant level.

We collected data on several measures related to the "stock" of new products per plant per year, but chose to use a time-to-market figure for our analysis, following most of the studies in this area. Thus, we define new-product flexibility in this context as the time (in months) starting from the earliest stage of design (customer product definition) and ending in the date when the first production batch of a "salable" product was made -- i.e. after prototypes and pilot low-volume runs were completed.

Note that our data refer to a new board design and not to minor changes to existing boards. A new board design often gives rise to a "family" of boards -- similar boards that evolve over time through minor modifications to the original design. A new board design is usually the effort of a team composed by people from design and manufacturing (sometimes marketing, although in our sample this is rather rare as boards are intermediate products), and typically takes several months. The mean time from design to production according to our data is about 12 months. Note though that there is a wide dispersion in the figures, as shown in Table 6.

V. The Implementation of Flexibility

Methodology: In Section II of this paper we built upon existing literature to propose several factors that may affect the implementation of flexibility. In this section we test the relative importance of each of these factors in the implementation of the three flexibility types described in the previous section. To keep the paper at reasonable length, we only discuss the main results of our analysis here. A more detailed discussion can be found in Suarez (1992).

From Section II recall that the factors affecting the implementation of flexibility (flexibility source factors) are: Production Technology, Production Management Techniques, Relationships with Suppliers and Distributors, Training and Skills of the Work-force, Employment Security and Compensation Policies, Product Design, Accounting and Information Systems. Typically, we measured a factor by several variables in our questionnaire in order to cross-check the answers and better capture that factor through multiple dimensions. For instance, production process technology was captured by the percent of total placements done by hand, percent of placements

using surface-mount technology, by the percent of machines linked by automatic transfer systems, and by the average age and value of the machines in the plant. A complete list of variables indicating the way each factor was operationalized can be found in Appendix 1. (Because of data reliability problems, we were unable to include in the analysis accounting and information systems as a factor.)

In order to determine the importance of a factor on a given flexibility type we proceeded as follows. First, we correlated the variables measuring each source factor with each flexibility type. We then selected the variables that showed the strongest correlation with each flexibility type. Next, we used these selected variables as predictors in a multivariate regression analysis with flexibility as the dependent variable. In this regression setting, we added three control variables: production volume, technological sophistication of the boards (measured as the plant's highest board density), and the number of production lines. Production volume helped us examine whether flexibility is an attribute of low volume, job-shop type of plants. The technological sophistication variable allowed us to study whether flexibility is more easily achieved by a plant producing simpler boards instead of more complex boards, or vice-versa. We added the number of production lines in order to determine whether a plant's greater flexibility (such as mix flexibility) is merely the result of having more production lines.

From the multivariate analysis, we determined which variables are significant predictors of each flexibility type. We kept variables with a significance level of 0.05 or less. In a couple of borderline cases we decided to keep the variables too, given that there was some theoretical support for their inclusion in the model. Tables 7, 8 and 9 summarize the results of this process of selecting predictors of flexibility. We briefly discuss our hypotheses and findings below.

Hypotheses and Findings: We discuss in turn each of the flexibility source factors described in Section II: Production Technology, Production Management Techniques, Relationships with Suppliers and Distributors, Training and Skills of the Work-force, Employment Security and Compensation Policies, and Product Design. If firms were using automated programmable technology to its fullest capabilities, we expected production technology to have a significant effect on mix flexibility and new-product flexibility. In general, more flexible production systems should enhance both flexibility types. Modern PCB assembly equipment is highly programmable and therefore can be used, at least theoretically, for a variety of board designs without much cost penalty. New equipment can also be linked to other parts of the factory (e.g. design and procurement), which should make it easier for a plant to handle a greater mix and come out more rapidly with new products. For instance, prototyping should be easier if one can quickly program machines for new jobs.

In reality, production technology turned out to be significantly related to mix and new-product flexibility, but with a pattern opposite to what we expected given the capabilities of the technology. A newer and more automated process in our sample tends to be associated with lower mix and new-product flexibility; this is evident from the negative sign of the first three variables listed in Table 7 and the positive sign of the variable average machine value in Table 9 (more modern machines are associated with longer time-to-market figures). This touches on a very important point: the fact that automated and programmable equipment in our sample tends to be used to run the largest production batches, instead of being used in a more flexible way. This finding is consistent with Jaikumar's (1986) observation regarding American flexible

manufacturing systems. (Jaikumar also found that Japanese firms used their FMSs more flexibly, although our sample is too small to test for country differences.) This fact may also explain why a more automated production technology turned out to be related to more volume flexibility (see Table 8). As we will see later, the three flexibility types appear to be related in a variety of ways that is not necessarily obvious.

We also expected "Japanese" or "lean" production management techniques to affect mix and new-product flexibility. Other studies (e.g. Cusumano 1985, Krafcik 1988, Womack, Jones, and Roos 1990, MacDuffie 1991) have shown that these techniques tend (among other things) to reduce machine set-up times and improve workers' awareness of and involvement in the production process -- characteristics that should make it easier to handle a more complex product mix and the introduction of new products. Since the PCB industry is relatively automated, however, it was unclear to us to what extent human-related factors would turn out to be important here compared to more labor-intensive contexts.

Following variables used in Krafcik (1988) and MacDuffie (1991), as expected, production management techniques do show some positive association with mix and new-product flexibility. The percentage of workers that participate in formal problem-solving group activities -- such as quality circles--is positively associated with both mix and new-product flexibility. This result is sensible given that involvement in these activities can broaden workers' knowledge about other areas of the production process. Broader knowledge and skills can then help workers understand and adapt to new tasks better, and improve their capacity to coordinate work.

We expected a close relationship with suppliers and subcontractors to affect positively all three types of flexibility. A plant may subcontract orders or models for which it has no adequate in-house capability. This practice can help to increase product variety, speed prototyping, or increase volume over in-house capacity without much cost penalty. Closeness to suppliers helps a plant to procure the right components when needed for assembly or prototyping; this is important because, if a plant lacks reliable suppliers, procurement may become problematic as product variety increases or new products are introduced frequently. Our a-priori expectations about the effect of this factor on each flexibility type is confirmed by the data. Note from Tables 7, 8, and 9 that the variable percentage of assembly subcontracted is significant and positively associated with mix, volume, and new-product flexibility.

We expected human resource management to be strongly related only to volume flexibility. Even though the PCB assembly industry is rather automated, the theoretical link between this factor and volume flexibility is so clear that we expected it to have a significant effect anyway. There are two issues here. On the one hand, plants that are not committed to permanent employment and that therefore tend to use temporary workers more freely should have an advantage in adapting to changes in volume. These plants can adjust their work-force level more easily to the existing volume demand. On the other hand, plants with wage structures linked to plant or division performance should also have an advantage in adapting to changing volume. Similar to the possibility of reducing the work-force number, the fact that wages are linked to performance automatically reduces the payroll burden in periods of low sales volume or crisis.

Our volume flexibility measure does seem to capture at least one of these effects. The percentage of wages related to plant or division performance shows a noticeable association with volume flexibility (note that if we use volume fluctuation instead this relationship vanishes). Because the volume flexibility measure penalizes plants with higher costs or lower quality levels, this relationship suggests that the volume flexibility measure proposed here is able to capture the cost advantage that plants with flexible wage schemes may have over fixed-wage plants, when it comes to demand fluctuations.

Finally, we expected the product-development process to be strongly associated with mix and new-product flexibility. In particular, plants that implement a policy of component reusability across board models should have an advantage in achieving mix and new-product flexibility. Higher component reusability creates the possibility of producing different models more quickly and cheaply by reducing the need to develop many new components from scratch and cutting down on production-preparation time and costs.

Component reusability turns out to be a significant predictor of mix and new-product flexibility in our sample. Higher component reusability seems to allow plants to handle a greater variety of both existing and new products. This relationship is sensible given that, other things being equal, a higher component count imposes a burden on the system: machines have to be programmed more often, workers have to be familiar with a higher number of parts, and other factors. This finding may have important policy implications for plants that need to deal with an increasing product variety or rapid product development requirements, since component reusability can be promoted by specific policies, such as lists of preferred components and other incentive schemes.

VI. Evaluating Flexibility: Implications for Strategy

In this section, we follow a twofold approach to evaluate flexibility. First, we consider the possible trade-offs between flexibility and quality or efficiency. In particular, we want to explore whether higher levels of flexibility tend to be associated with higher (or lower) levels of cost and quality. Second, we look at the relatedness among flexibility types. As we will see, different flexibility types seem to relate to each other in specific ways that have important strategic implications.

Trade-Offs with Cost and Quality

First, we want to examine evidence to help assess the desirability of flexibility. We explore the possible drawbacks of increasing flexibility by analyzing the relationship between each flexibility type and two crucial parameters of any production system: cost and quality. We expect that any drawbacks to more flexibility will tend to be reflected in higher costs or lower quality levels. Note that we consider only mix and new-product flexibility in this analysis. From Section IV recall that our measure of volume flexibility already penalizes plants with higher cost or lower quality levels.

We measured quality in two ways: as the number of non-repairable boards per million at the post-assembly check (DEFECT), and as the percentage of boards that undergo some repair through the assembly process (SMREPAIR). These two measures are complementary. Some plants present a low post-assembly-check defect figure but

they achieve it through extensive board repair during assembly. During our visits, we saw substantial differences across plants in the amount of repairs undergone by the boards being assembled. Table 10 below displays basic statistics about the two measures of quality.

As in many studies of quality with samples from different countries (see, for instance Garvin 1988), quality figures in our own sample vary substantially. Defects per million at the post-assembly check vary from zero to 14,000 measured at the same check point. The percentage of boards that undergo some repair also varies widely across plants. "Repairs" in our question included all types of repairs, including routine repairs such as fixing solder shorts and opens, or misplaced components.

Note from the correlation coefficients presented in Table 10 that the two measures of quality seem to be unrelated to either mix or new-product flexibility. None of the correlations in Table 10 is significant at the 0.05 level. We also plotted each pair of variables and then transformed the variables (usually a log-transformation) in order to explore for possible non-linear relationships. No signs of such type of relationships were found in our data. Plants that score high on either mix or new-product flexibility do not seem to correspond to lower- (or higher-) quality plants in any systematic way. Figure 1, plotting mix flexibility against the number of defects at the post-assembly check, is a typical plot of quality versus flexibility.

With regard to the relationship between mix flexibility and cost, because of confidentiality reasons, we were unable to get a detailed account of each plant's cost structure. Instead, we rely on a common industry measure that appears to be a reasonable metric for comparisons across plants: cost per component placed. Our question asked respondents to include both direct and indirect costs, giving us the percentages corresponding to each of them. Summary statistics of these data are shown in Table 11 below.

Note the wide dispersion in the answers. A few plants reported cost per placement figures of less than U.S.\$0.01, while one plant reported a figure of roughly U.S.\$0.40. Recall that our sample includes plants producing for different final applications and with different production volumes. Other work supervised by one of the authors (Altman, 1992) uses regression analysis and activity-based costing to analyze printed circuit-board placement costs. This work provides useful explanations for understanding such large differences in placement costs. Table 11 also reports correlation coefficients between cost per placement and two measures of a plant's volume: number of boards per year and number of components placed. The coefficients are rather high and one of them is significant at the 0.05 level, suggesting -- as expected -- that plants with higher volumes tend to present lower cost figures. Note also from the table that the correlation of cost with percentage of through-hole placement (as opposed to SMT placement) is not significant. A higher percentage of through-hole placement does not seem to be associated with higher cost per placement in any strong way.

The table also reports the correlation coefficients between cost per placement and mix as well as new-product flexibility. None of the correlations is significant and both are rather weak. As we did with quality, we explored for the possibility of non-linear associations which are not captured by the correlation coefficient. No such associations were found in our data. As an example, Figure 2 plots our aggregate

measure of mix flexibility against cost per placement. The two variables seem to be orthogonal to each other.

Thus, as far as our data is concerned, we do not detect any significant overall trade-offs between mix flexibility and either cost or quality. This seems to be in line with other studies on automobiles and air conditioners which suggested that high quality, instead of being costly, is often associated with low costs or high levels of productivity, and that improvements in mix flexibility do not seem to increase costs or worsen quality levels to any great extent (Garvin, 1988; Krafcik, 1988; Womack, Jones, and Roos, 1990; MacDuffie, 1991).

Relatedness Among Flexibility Types

We suggested earlier that different flexibility types tend to be achieved through different configurations of and emphases on production technology, production management techniques, relationships with suppliers, human resource management, and product development processes. If the different flexibility types require different configurations on all these factors, perhaps it is very difficult to achieve all of them at once. A truly flexible plant -- that is, a plant which is flexible on all dimensions -- may be impossible to achieve, even though the term "flexible factory" is widely used.

But, while one objective of this study was to examine if trade-offs existed between two or more types of flexibility, during the data analysis, instead of trade-offs in the conventional sense, we began to see relatedness. In other words, flexibility types seem to relate to each other rather than to work against each other, and as we will see below, this relatedness has various implications for manufacturing strategy.

Mix Flexibility and Volume Fluctuations: Let us begin with the relationship between mix and volume fluctuations. We include volume fluctuation in the analysis here because, as we said before, the literature to date has not been very careful in distinguishing volume fluctuation from volume flexibility. In addition, volume fluctuation turns out to have a significant relationship with mix flexibility. As we will see below, mix-flexible plants are best at avoiding volume fluctuations.

Figure 3 below plots the relationship between mix flexibility and volume fluctuation. Note in the plot that two groups could be distinguished, one grouping the thick cluster of the upper left hand side of the plot and the other grouping the sparse points that lie outside of that thicker cluster and that suggest a positive-slope line. The interpretation is not trivial. The group outside the thick cloud does not seem to be composed of similar plants in any respect, at least not in terms of geographical region or boards' final application. However, the plot clearly shows that all plants scoring high in the aggregate measure of mix flexibility (say, higher than 5.6 in the plot) present rather low volume fluctuations -- a ratio of highest to lowest monthly production of less than 2.2. Conversely, plants which present high volume fluctuations tend to present low-to-intermediate mix flexibility figures. This pattern (which is supported but not completely captured by the negative correlation of -0.18 between both variables) has an important strategic implication: plants with high (or higher) mix flexibility are best at avoiding volume fluctuations.

Thus, plants that are able to achieve greater levels of mix flexibility may enjoy the benefits of a more stable production flow. This is mainly the result of the

"cushion" effect provided by a broader mix -- the old story of not keeping all the eggs in the same basket. A broader mix provides a cushion against the fluctuation in any given family of boards. For instance, plants that can switch among boards for many product variations (for example, several VCRs and camera models, or different world-processor and computer models) will not be so adversely affected if the demand for one product line shrinks unexpectedly.

By extrapolation, all the factors that increase mix flexibility will tend to increase production stability. For instance, recall that closeness to suppliers and subcontractors was identified as a source of mix flexibility. Similarly, closeness to suppliers and subcontractors will tend to have a stabilizing effect on production volume. The effect here is twofold. On the one hand, a close relationship with suppliers and subcontractors will tend to increase mix flexibility and a plant will benefit from the cushion effect discussed above. On the other hand, subcontractors themselves may be a source of cushion, as firms may increase or decrease subcontracting in response to demand fluctuations, thus keeping a plant's in-house volume more stable.

The policy implications of this pattern are easily visualized. By strengthening mix flexibility, plants are likely to smooth their production flow. A more stable production flow, other things being equal, is a desirable attribute for most plants, even those considered to be "flexible." More importantly, by identifying the factors strongly associated with mix flexibility, we have shed light on specific strategies that a plant can follow in order to smooth its production flow.

Mix Flexibility and Volume Flexibility: What happens when we consider volume flexibility instead of volume fluctuation in this analysis? A low correlation coefficient of -0.05 between mix flexibility and volume flexibility and a plot that provides no visual indication of any relationship (not shown here) suggest that the two variables are not related. That is, mix flexibility appears to be a strategic cushion for volume fluctuations but does not have the same relationship with volume flexibility. This is consistent with our earlier results. Recall from Tables 7 and 8 that we found that the factors strongly associated with volume flexibility are for the most part different from those affecting mix flexibility. Thus, one would expect these two flexibility types to be unrelated.

Theoretically, however, one can think of a possible association between mix and volume flexibility. We have shown that mix-flexible plants are best at avoiding volume fluctuations. It follows that mix-flexible plants should not need as much volume flexibility as less mix-flexible plants do, as the latter ones have to cope with higher volume fluctuations. This would imply a negative correlation between mix and volume flexibility. Such correlation is not supported by our data, but it is an interesting theoretical possibility that should be explored further in future studies.

Mix Flexibility and New-Product Flexibility: Let us now look at the relationship between mix and new-product flexibility. With a correlation coefficient of -0.52 , significant at the 0.01 level, the measures for the two flexibility types present a rather strong negative correlation. Recall our measure of new-product flexibility is design to production time: a smaller number implies greater new-product flexibility. Our finding suggests that high mix-flexible plants tend to have shorter design to production times. In other words, both types of flexibility tend to go together in the sample, rather than showing a trade-off. Figure 4 below supports this relationship.

Several plants in the sample are able to achieve high levels of both types of flexibility (high mix flexibility and short design cycle times: upper left corner of the plot). Other plants seem to become increasingly less flexible in both dimensions.

This again has important strategic implications. Our data show these two flexibility types tend to reinforce each other. Given our analysis in Section V, this does not come as a surprise. We have seen that the factors affecting more strongly each of the two flexibility types tend to be the same. Several of the factors that proved significant in achieving mix flexibility were also significant for new-product flexibility. For instance, component reusability turned out to be an important explanatory variable for mix flexibility. It also turned out to be important in the analysis of new-product flexibility (we had stated this as an a-priori hypothesis). Similarly, worker involvement in problem-solving group activities turned out to be important for both types of flexibility. Thus, it seems that mix and new-product flexibility, for those plants that manage them well, tend to go hand in hand.

Consider now some implications of this. Some authors, led by Skinner (1974), have championed the idea of a "focused factory" as a way of improving a factory's performance. A focused factory is one that has trimmed down its product variety in order to specialize in a narrower product line. Our data show that this policy may have consequences not only for mix flexibility (which is reduced almost by definition when a plant gets more focused), but also for new-product flexibility. Plants that have decided to be focused -- i. e. to produce only a few products -- may be implicitly sacrificing new-product flexibility and leaving themselves open to volume fluctuations. In the long term, this may jeopardize a plant's ability to maintain high levels of capacity utilization and thus to operate profitably.

A second implication comes from the mutually reinforcing effect that mix and new-product flexibility exert on each other over time. Plants that stress rapid new-product introduction will naturally tend to increase their mix flexibility as time goes by -- assuming that the boards' rate of obsolescence is not too high. That is, not only will both flexibility types tend to go together because they are affected by a common set of factors, but also rapid design cycles may reinforce a plant's mix flexibility over time. This dynamic, in turn, will tend to smooth production volume fluctuations, due to the cushion effect of mix flexibility on volume fluctuations. Thus, the relatedness among these three flexibility types may have powerful consequences for plant performance in the long run.

Volume Flexibility and New-Product Flexibility: Finally, let us examine the relationship between volume flexibility and new-product flexibility. A randomly distributed plot and a low correlation coefficient of -0.11 suggest a weak and non-significant relationship between the constructs. This is again consistent with our previous results. As with mix flexibility, we did not expect volume flexibility to be correlated with new-product flexibility. Recall from Section V that the factors that turned out to be important predictors of volume flexibility in our analysis tend to be different from those factors that are strongly associated with new-product and mix flexibility.

VII. Conclusion

In summary, our findings include several empirical results regarding the implementation of flexibility:

- (1) A newer and more automated production process tends to be associated not with more flexibility but with less flexibility in terms of product mix or new product introductions. This adds support to the observation that many users of flexible manufacturing systems do not utilize the flexibility inherent in the technology to produce mixes of different products, but rather tend to use even programmable automation for large-batch production.
- (2) Non-technology factors, such as high involvement of workers in problem-solving activities, close relationships with suppliers, and flexible wage schemes for plant workers, are positively correlated with combinations of new-product, mix, or volume flexibility.
- (3) Component reusability, which reduces the need to accommodate many different parts, even for different products, is significantly correlated with product-mix and new-product flexibility.

We can also make several observations regarding the strategic value of flexibility in manufacturing:

- (1) High mix or new-product flexibility does not seem to involve a penalty such as poorer quality (more defects) or increased costs. This is consistent with other research that has found high quality and low costs tending to go together, even with relatively complicated product mixes.
- (2) Mix flexibility and new-product flexibility are mutually reinforcing and tend to be supported by similar factors, such as components reuse or worker involvement. High mix-flexible plants also tend to have shorter design-to-production times.
- (3) Mix flexibility appears to be a useful way to avoid usually unwanted fluctuations in production volume. It follows that all factors which improve mix flexibility should contribute to stability in production levels.

Our analysis of flexibility has allowed us not only to know more about each flexibility type in isolation, but also to identify a pattern of relatedness among the three flexibility types studied. As we have seen, two flexibility types -- for product mix and new products -- tend to be mutually reinforcing and to move statistically in the same direction. Volume flexibility appears to be orthogonal to the other two flexibility types (although there exists a possible theoretical negative correlation between mix and volume flexibility). We have also seen that this interrelatedness seems to have important strategic implications. Managers need to think carefully about which types of flexibility they want, and evaluate several possible ways to achieve each flexibility type. Managers should also be aware that the factors and policies that affect one flexibility type may have little or no effect on a different flexibility type. Or alternatively, as seen with mix and new-product flexibility, two flexibility types may reinforce each other.

The relatedness among flexibility types that we propose in this paper can be summarized graphically using a simple causal loop diagram such as the one in Figure 5 (see Senge 1990 for a discussion of this type of diagram). In the vocabulary of system dynamics, there is a reinforcing (or amplifying) feedback process between mix flexibility and new-product flexibility. Mix flexibility, in turn, affects volume fluctuation through the cushion effect discussed above. The diagram also depicts the theoretical link between volume fluctuation and volume flexibility.

While this paper has advanced the state of empirical research on manufacturing flexibility, our results should be taken as no more than a preliminary step toward understanding the complex, multi-dimensional phenomenon of flexibility at the plant level. Because of the special characteristics of the PCB industry where the data were gathered, and the relatively small size of the sample, additional studies should be conducted in other industries before we can determine whether or not these results apply to other manufacturing contexts. As more industry studies are added, and new and better measures developed, we hope to develop a clearer image of what a truly flexible factory looks like in practice and what benefits it provides to management.

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Table 1. Number of Plants Producing for Each Final Application by Geographical Region.

Final Application of Assembled Boards	U.S.	Europe	Japan	Totals
Automotive	4	2	1	7
Consumer Electronics	0	5	5	10
Computers	7	3	3	13
Measuring Instruments/Medical Equipment	4	0	0	4
Telecommunications	2	2	2	6
Business Equipment	1	0	0	1
Totals:	18	12	11	41

Note: Many plants produce boards which are used in more than one final application listed in the table. In these cases, we classified a plant in all segments it produces for. Thus, the sum of the numbers of the table adds to more than our sample size.

Table 2. Summary Statistics for Four Measures of Mix Flexibility.

	Number of Board Models	Number of Board Sizes	Range of Board Density	Number of Product Categories
Number of Cases	31	28	31	30
Minimum	2	2	0.095	1
Maximum	2002	1000	21.200	8
Mean	385	125	2.448	3.03
Standard Deviation	570	229	3.842	2.01
Pearson Correlations:				
with BRDMOD90	1	0.53	0.19	0.40
with NBBRDSIZ		1	0.44	0.69
with RNDENSIT			1	0.59
with PRDCATEG				1

Table 3. Result of the Principal Components Analysis of Mix Flexibility

Variable	First Component	Second Component	Third Component	Fourth Component
Eigenvectors:				
Logarithm of Number of Board Models	0.52	0.04	-0.56	0.64
Logarithm of Number of Board Sizes	0.53	-0.28	-0.35	-0.72
Logarithm of Range of Board Density	0.47	0.80	0.34	-0.14
Logarithm of Number of Product Categories	0.48	-0.52	0.67	0.23
Eigenvalues:				
% Variance Explained	2.92	0.48	0.43	0.16
	0.73	0.12	0.10	0.05

Table 4. Ratio of Highest to Lowest Monthly Board Production, 1989-1991.

	Production Volume Range 1989	Production Volume Range 1990	Production Volume Range 1991	Production Volume Fluctuation
Number of Cases	23	24	27	27
Minimum	1.1	1.1	1.1	1.1
Maximum	17.0	6.0	8.0	9.9
Mean	2.8	2.1	2.4	2.6
Standard Deviation	3.2	1.1	1.6	1.8
Median	2.0	1.9	2.0	2.0

Table 5. Summary Statistics of Volume Flexibility

Volume Flexibility (3-D Measure)	
Number of Cases	24
Minimum	2.120
Maximum	9.880
Mean	5.570
Standard Deviation	2.170
Median	5.325
Pearson Correlations with Production Volume Fluctuation	0.22

Table 6. Summary Statistics for New Product Flexibility

Design Cycle Time (months)	
Number of Cases	29
Minimum	2
Maximum	36
Mean	13.3
Standard Deviation	8.6
Median	12.0

Table 7. A-Priori Hypotheses and Results Regarding Mix Flexibility Implementation

Factor	Expected Relationship	Significant Variables / Sign
Production Technology	A newer, more sophisticated technology will increase mix flexibility in this industry, since newer PCB assembly equipment is highly programmable.	Percentage of SMT placement (-); Percent of machines linked by automated transfer systems (-); Average machine value (-).
Production Management Techniques	So-called "Japanese" production management techniques will tend to increase mix flexibility by reducing set-up costs, and increasing workers' authority and coordination.	Percentage of workforce involved in quality circles (+);
Supplier and Subcontractor Relationship	A close relation with suppliers and subcontractors will increase mix flexibility, as subcontractors may be able to handle some of the variety imposed on a plant.	Percent of assembly subcontracted (+).
Human Resource Management	No strong effect expected, given the automated nature of the industry. In general, workers with better and broader skills and training should tend to increase mix flexibility.	Percentage of workers that regularly use computers to perform their work (+).
Product Development Process	Higher component reusability across board models will increase mix flexibility.	Number of components per board model (-).

Table 8. A-Priori Hypotheses and Results Regarding Volume Flexibility Implementation

Factor	Expected Relationship	Variables Involved / Expected Sign
Production Technology	No strong relationship was expected. However, newer and programmable machines can be expected to increase volume flexibility.	Percent of machines linked by automated transfer systems (+).
Production Management Techniques	No strong relationship was expected.	
Supplier and Subcontractor Relationship	A close relation with suppliers and subcontractors will increase volume flexibility. Subcontractors may be asked to absorb some of the volume fluctuation.	Percent of assembly subcontracted (+).
Human Resource Management	"Permanent employment" and fixed-wage labor policies will decrease volume flexibility by making it costlier for a plant to adjust to volume fluctuations. More intensive use of temporary workers will increase volume flexibility.	Percent of wages related to plant or division performance (+). Number of parts placed per person doing hand assembly (-).
Product Development Process	No strong relationship was expected.	

Table 9. A-Priori Hypotheses and Results Regarding New Product Flexibility Implementation

Factor	Expected Relationship	Variables Involved / Expected Sign
Production Technology	A newer, more sophisticated technology will increase new product flexibility, as newer PCB assembly equipment can be easily programmed to run new jobs.	Average machine value (+).
Production Management Techniques	The new production management techniques will tend to increase new product flexibility by reducing set-up costs, and increasing workers' authority and coordination.	Percentage of workforce involved in quality circles or related groups (-).
Supplier and Subcontractor Relationship	A close relation with suppliers and subcontractors will increase new product flexibility. Suppliers can provide needed components promptly and subcontractors can help with prototypes and low-volume trial runs.	Percent of assembly subcontracted (-).
Human Resource Management	No strong relationship expected due to the level of automation in the sample. However, one may expect a better trained and educated workforce to increase new product flexibility.	
Product Development Process	Higher component reusability across board models and greater involvement in product development will increase new product flexibility.	Number of components per board model (+).

Table 10. Summary Statistics for Quality Measures

	Number of Defects at Post-Assembly Check	Percent of Boards that Undergo some Repair in the Process
Number of Cases	27	29
Minimum	0	0.01
Maximum	14000	100
Mean	2436.3	27.3
Standard Deviation	3691.5	26.5
Pearson Correlations with:		
Mix Flexibility (aggregate measure)	0.13	0.01
New Product Flexibility	-0.05	-0.14

Table 11. Summary Statistics for Cost Per Placement (U.S. Dollars)

	Cost per Placement	% Direct Costs	% Indirect Costs & other Allocations
Number of Cases	25	22	22
Minimum	0.002	11	9
Maximum	0.400	91	89
Mean	0.121	47.3	48.1
Standard Deviation	0.122	22.7	24.2
Median	0.090	49.0	41.0
Pearson Correlations with:			
Mix Flexibility (aggregate measure)	0.21		
New Product Flexibility	0.07		
Production Volume in Boards per Year	-0.50		
Production Volume in Components Placed per Year	-0.37		
with percent of through- hole placement	0.23		

Figure 1. Plot of Mix Flexibility versus Number of Defects Per Million at Post-Assembly Check.

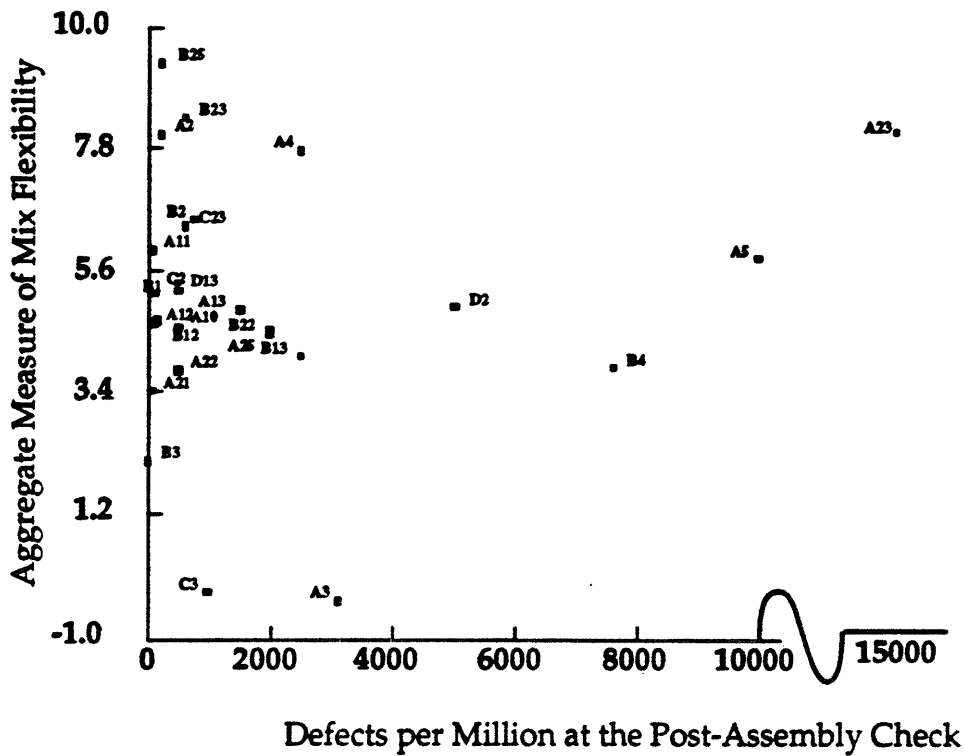


Figure 2. Plot of Mix Flexibility versus Cost Per Placement

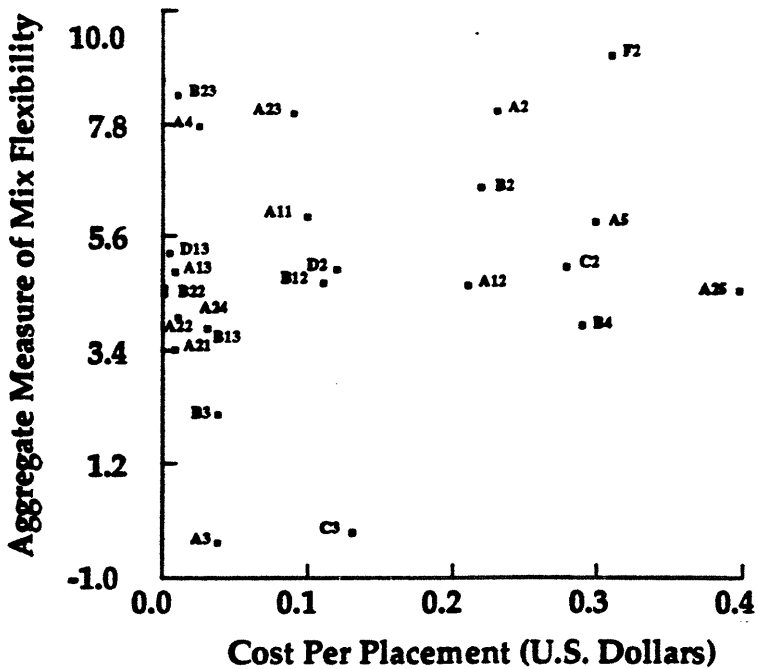


Figure 3. Plot of Mix Flexibility versus Volume Fluctuation

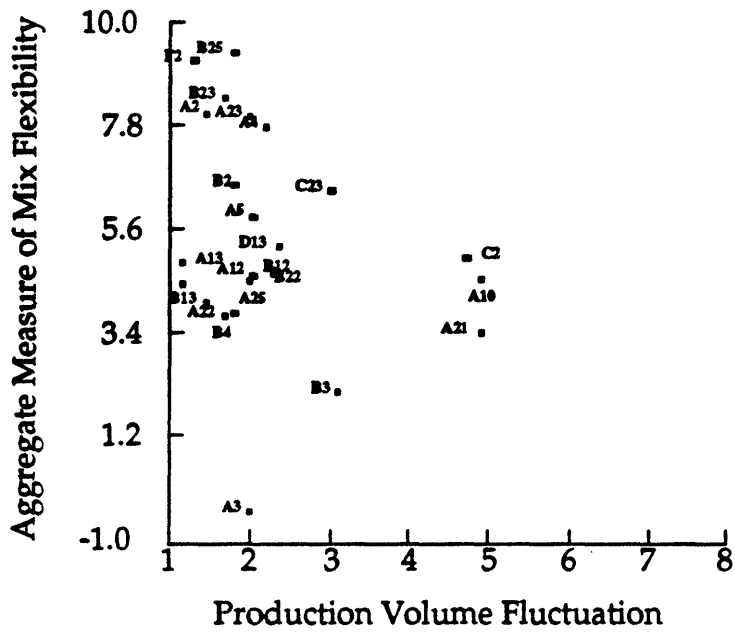


Figure 4. Plot of Mix Flexibility Against New Product Flexibility

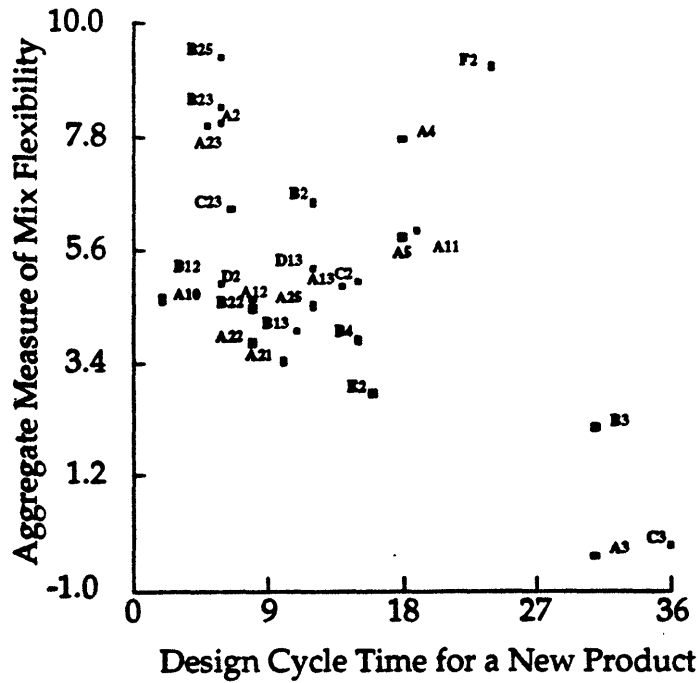
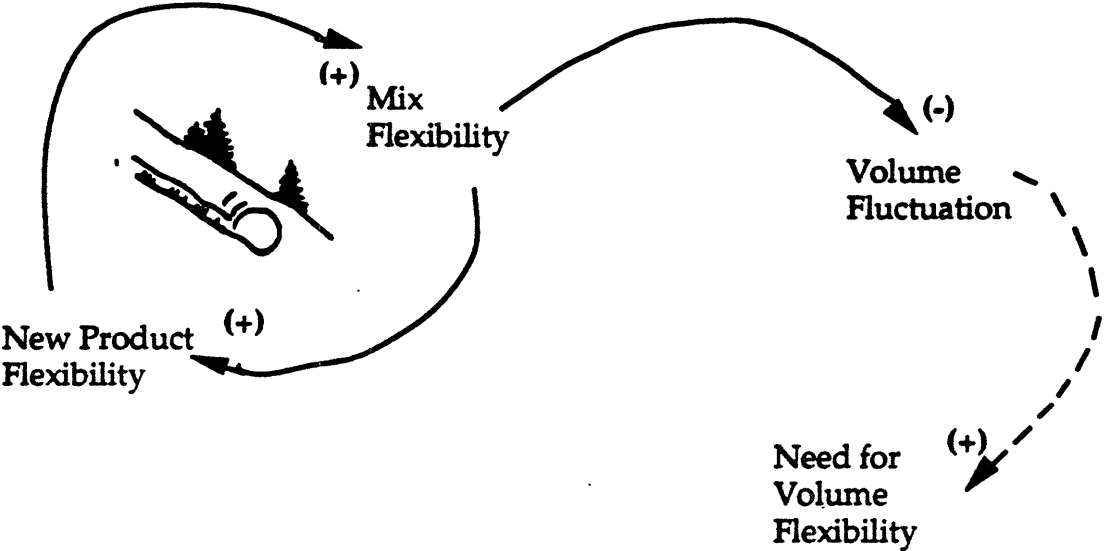


Figure 5. A Summary Representation of the Relatedness Among Flexibility Types.



Appendix 1

We have operationalized each of the factors or constructs mentioned above as follows.

Production Process Technology

- Percent of total placements done by hand (PCTHAND).
- Percent of placement done using SMT (PCTSMT).
- Percent of machines linked by automatic transfer systems (PCCONVEY).
- Average age (years) of three types of machines: high speed placement, high precision placement, and soldering (AGEAVERG).
- Average original value per machine in thousands of U.S. dollars. It considers the same three types of machines: high speed placement, high precision placement, and soldering (VALUEAVG).

Production Management Techniques

- Number of organizational levels in the plant (ORLEVEL).
- Average 1990 Inventory of components, raw boards, WIP, and assembled boards (AVRINV).
- A measure of how much responsibility resides with production workers or other low-rank staff, on a 1 to 7 scale (AVRELYON).
- Average set-up time for a new part number (hours) in high speed machines, high precision machines, and soldering. Our variable (AVGSETUP) is the mean value of these set-up numbers.
- Average downtime per week (hours), computed in a similar fashion to AVGSETUP.
- Percentage of the workforce involved in official problem solving group activities, such as quality circles (QCINVOLV).

Relationship with Suppliers and Distributors

- Average on a 1-to-7 scale indicating the extent to which the plant offers technical assistance to suppliers in six different dimensions (TASSSUMM)
- Number of hours of a plant's employees time spent working at suppliers sites plus number of hours of suppliers' employees spent in the plant's site, 1990 (TASINOUT).
- Percentage of assembly subcontracted to suppliers (SUBCONTR).

Human Resource Management

- Average hours of training received by workers during 1990 (AVTRAIN).
- Percentage of workforce involved in training programs, 1990 (PTTRAINED).
- Percentage of workforce with more than primary education, 1990 (NOPRIMARY).
- Average number of components placed by each person doing hand assembly (HANDNUMB).
- Percentage of production workers that have access to and regularly use a computer terminal to perform their work (TERMINAL).
- A dichotomous variable indicating if permanent employment is a plant's policy (PERMANT).
- Percentage of wages related to plant or division performance (PERFWAGE).
- Average percentage of temporary production workers employed in the plant (TEMPPCT).
- A 1-to-7 scale measuring the availability of temporary skilled workers for the plant (TEMPAVAI), where 7 is readily available.

Product Development Process (Product Design)

- A measure of the extent to which a plant uses common components across boards (COMPRMOD), computed as the total number of different components used divided by the total number of board models assembled.
- Average percentage of components currently used in two or more board models (COM2PLMD).
- Average percentage of new components used in new board models--i.e. components that had not been used in other models before (NEWCOMP).
- Respondent assessment of the plant's degree of involvement in the design process for new boards (DESINVOL).