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The Impact of New Manufacturing Requirements on Production Line Productivity and Quality at a Focused Factory

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Since Skinner's (1974) seminal work, the manufacturing literature has argued that focused factories should typically out-perform general purpose production facilities. Most of the writing on manufacturing focus, however, emphasizes stable manufacturing environments (Stobaugh and Telesio 1983; Hayes and Wheelwright 1984, p. 90, p. 108; Hayes and Clark 1985; Hill 1994, p. 152).Yet, most factories inevitably face changes in their requirements, so that a focused factory eventually will need to perform tasks that differ from its original tasks. This paper examines the relationship between manufacturing focus and factory performance in such a dynamic environment. Specifically, we examine how the performance of a focused factory's production lines changes after the factory changes its manufacturing requirements. We define focus in terms of manufacturing requirements and measure changes in focus through variables that affect production line activities, including part mix and production volume, at focal and downstream production lines. Our conceptual and empirical analyses help place discussions of focused factories into a more dynamic environment.

Our predictions concerning the relationships between change in manufacturing requirements and production line performance draw from a conceptual model of manufacturing activities that includes two dimensions: limited manufacturing routines and absorptive capacity for adaptation. We base the model on the organizational nature of production line activities. A production line is an organizational unit, which one can view as a collection of self-sustaining routines (Nelson and Winter 1982). Organizations and their sub-units such as production lines often find it difficult to depart from prevailing routines. We draw most directly on the concept of absorptive capacity, which is the ability to recognize, evaluate, assimilate, and utilize new knowledge (Cohen and Levinthal 1990). We argue that manufacturing focus sometimes creates conditions under which production lines lack the absorptive capacity to adapt effectively to requirements unrelated to their existing focused task. We hypothesize that a change for which a line possesses adequate absorptive capacity does not reduce the performance of the line, but absence of adequate absorptive capacity leads to a decline in performance.

We test the hypotheses at fifteen production lines of a well-known focused factory of the Copeland Corporation of Sidney, Ohio, using primary output and performance data over a four-year period during which the company changed the manufacturing requirements of the production lines. The factory is located at Hartselle, Alabama. Consistent with the requirements of a theory testing case study, the conceptual variables of the hypotheses are general constructs, while the operational variables are specific to the site. Our statistical analysis both illustrates the limits of change and identifies some paths through which firms may undertake effective change.

1. Literature Review

Studies seeking empirical evidence on the benefits and costs of factory focus include case studies and statistical studies. Several of the writings on performance benefits of focusing efforts draw from case observations of factories. Based on a study of about fifty plants in six industries, Skinner (1974, p. 116) comments that his research makes it clear that, 'the focused factory will outproduce, undersell and quickly gain competitive advantage' over a general-purpose factory. Ruwe and Skinner (1987) report improvements along several dimensions of operational performance after focusing at a manufacturing plant of the Copeland Corporation. Hayes and Wheelwright (1984, p. 34) cite two case studies in which focus appears to be associated with lower manufacturing costs. More recently, Ferdows (1997) observes that superior manufacturing firms are building global networks of focused factories, but comments that it is difficult to quantitatively assess the impact of the approach. In an Andersen Consulting study, Harmon (1992) reports that operating performance has improved by up to 80 percent through implementation of focus in about 2,000 factories. In a McKinsey and Company study of about 40 firms, Rommel, Kluge, Kempis, Diederichs, and Bruck (1995) find that the firms with focused factories enjoyed a higher growth rate, greater productivity, and higher return on sales than their non-focused competitors.

In addition to case studies, a few statistical studies have studied how product variety affects manufacturing performance, producing varying results. Some researchers have observed positive relationships between manufacturing performance and measures of limited product variety. In a study of an automobile component manufacturer, Banker et al. (1990) find that a greater number of moving parts in a mold had a significant, detrimental impact on the costs of supervision, quality control, and tool maintenance. Using data from the International Assembly Plant Study[1] MacDuffie, Sethuraman, and Fisher (1996) find that two measures of product variety, including greater parts complexity and option content, have a negative impact on productivity, while two others, including model mix complexity and option variability, have no significant impact. Further, they find no statistically significant relationship between quality and any measure of variety. In a longitudinal study, Anderson (1995) uses a measure of product variety she derived through factor analysis of product and process engineering attributes of textile manufacturing, finding a negative correlation between product variety and performance. In a study of U. S. manufacturing plants, Brush and Karnani (1996) find that cost declines with greater product focus, but has no relationship with process focus. Other researchers have found little effect of product variety on manufacturing performance. Hayes and Clark (1985) find no significant relationship between product variety and cost in a study of twelve factories in three industries. Kekre and Srinivasan (1990) examine the market benefits and cost implications of broader product lines using the Profit Impact of Marketing Strategies (PIMS) data base, and uncover little empirical evidence that manufacturing costs increase with product variety. Foster and Gupta (1990) examine the manufacturing overhead cost factors in the electronics industry, and observe little association between manufacturing overhead costs and cost factors such as number of parts, product line breadth, and number of suppliers. Thus, even cross-sectional studies of manufacturing focus have produced mixed results.

Although ambiguous, the empirical evidence concerning the impact of manufacturing variety on manufacturing performance has several important implications for research on factory focus. First, while case studies examining specific focusing efforts suggest superior factory performance, the conclusions often come from broad observations rather than precise measurements. On the other hand, , most of the precise measurements mentioned above do not address whether the manufacturing plants that were studied engaged in the managerial exercise of focusing, which involves determining limited manufacturing requirements and tailoring the manufacturing systems to these requirements. Thus, unobserved heterogeneity concerning the design of manufacturing systems may limit the interpretation of the statistical results.

Second, it is difficult to arrive at a generalizable empirical observation about the relationship between product variety and performance from these studies. One reason concerns the basic economics of the firms examined. The studies involve industries that have different underlying economies and diseconomies of scale and scope. Further, theoretical economic models have been unable to include the number of products in the cluster of complementary elements that maximize the profits of most modern manufacturing firms (for example, Milgrom and Roberts 1990). A second reason concerns the metrics used. The studies differ in the variables used as measures of performance as well as product variety. If one divides these studies into two groups depending on the type of measure of product-variety used, a striking characteristic emerges. Studies that use relatively simple measures of product variety find little correlation between variety and cost (e.g., Hayes and Clark 1985; Kekre and Srinivasan 1990; Foster and Gupta 1990), while studies using more sophisticated measures of product variety find a positive relationship between limited variety and performance (e.g., Banker et al. 1990; Anderson 1995; MacDuffie, Sethuraman, and Fisher 1996). Both of these reasons speak to the need to identify relevant measures of focus in specific industrial settings.

Third, most studies have used product-oriented variables to measure focus. Strikingly, few empirical studies examine focus on other dimensions, particularly the congruence between the manufacturing capability of a factory and its competitive deliverable. Only recently have some researchers attempted to measure this effect numerically using perceptual data (Pesch and Schroeder 1996; Berry and Bozrath 1997). Because focus itself does not have a measure with statistical validity and reliability, it is not surprising that the relationship between performance and focus remains elusive to statistical assessment.

In the next section of the paper, we present a conceptual model of factory focus that we hope will help clarify the discussion of manufacturing focus in the literature and facilitate empirical research. In the subsequent sections we apply the model to study the impact of change of manufacturing requirement on production line performance at a manufacturing facility.

2. Conceptual Model of Factory Focus

We propose a conceptual model of manufacturing activities that includes two dimensions: limited manufacturing routines and absorptive capacity for adaptation. The model suggests two propositions concerning adaptation to changed manufacturing requirements.

2.1 Limited Manufacturing Routines

One can view the manufacturing task of a factory as developing and exploiting a set of manufacturing skills deemed necessary by the firm's strategy. We can think of the manufacturing skills as manifestations of the corporate core competencies (Prahalad and Hamel 1990) that are resources of the firm (Wernerfelt 1984). Indeed, Prahalad and Hamel argue that organizational learning about how to coordinate diverse production skills is a key element of core competence. The skill-based view of manufacturing tasks has the appealing characteristic that it provides a theoretical basis for defining focus, because the view connects closely with the evolutionary theory of organizations proposed by Nelson and Winter (1982). Skills of a firm have, as one of their components, the manufacturing skills of its facilities. Similarly, these facility skills comprise the skills of the production lines and related support functions. Following Nelson and Winter's view that routines are the skills of an organization, we equate skills of a production line with the routines executed at the line. Examples of routines at a production line include technological processing routines, information flow routines, material flow routines, and manufacturing support routines. The general description of routine performance of a production line in equilibrium contains two elements. First, the line must retain in its repertoire all routines actually invoked in the given state of equilibrium operation. Second, the line must know what routines to perform when. That is, the operators of the line must be able to receive, interpret, and respond to messages by executing appropriate routines.

The key concept underlying the idea that routines are the skills of an organization is that organizations remember by doing. Thus, firms remember production line skills through executing them. The execution of a production line routine involves the effective integration of a number of component subroutines often accomplished without conscious overview; that is, without requiring the explicit attention of management. Since the purpose of focus is to excel in a skill, and since skills are combinations of routines that production lines remember by doing, achieving focus in the task of a production line requires that the task be repetitively executed. Major tasks for management in focusing a production line are to design a set of routines that are coherent components of a specific targeted skill set, and to establish a process in which employees, machines, and systems can repeat the routines without having to explicitly reconsider each step each time it is executed. Hence, a focused manufacturing facility will restrict the number of manufacturing routines required of its operators. In general, the fewer the routines, the more focused a facility.

A firm can limit the number and variety of routines at a factory's production lines by limiting the demands on the factory itself. In the late 1970s to mid 1980's, various opinions emerged about how to limit the demands on a factory. Several of these are illustrated in Table 1 which draws from published empirical and conceptual work (Hayes and Schmenner 1979; Schmenner 1982; Hayes and Wheelwright 1984, pp. 90-108; Hill 1989, p. 102). The classification system in the table for focusing factories examines the firm's portfolio along one of a set of alternative dimensions and then assigns concise sections of the portfolio to separate factories. However, factories with limited portfolios along a particular dimension may contain conflicts within other dimensions. For example, along the market dimension, a product-focused factory may serve several markets that have different price expectations, regulatory standards, and delivery requirements. Consequently, potentially conflicting routines may exist even within a seemingly well focused facility.

********** **Table 1, Table 2, and Figure 1 about here** **********

We can analyze the conflict in demands on a factory by treating the dimensions of focus as complementary at the level of the individual factory. We draw from Wheelwright (1979), and a Delphi survey of an expert panel by Pesch (1996) to suggest that at the factory level, focus involves limiting the operating routines of the factory on a continuum along each of a set of complementary dimensions. For example, consider the positions of two hypothetical annealing facilities, Factory F and Factory F_1, along each dimension of focus as shown in Table 2 and Figure 1 below. Table 2 notes different choices along the focusing dimensions that we list in Table 1, while Figure 1 depicts the complementary nature of the choices as a multidimensional map. Each spoke in the figure represents a dimension. A point closer to the center represents greater uniformity of demands than a point further away from the center. The chosen response vectors of a factory describe the extent of focus at the factory. In this example, Factory F is more focused than Factory F_1.

The focusing dimensions assist manufacturing managers only if they know the specific levers that affect change along each dimension. We call these levers the 'controlling determinants' of focus. As we have argued in our review of the literature, controlling determinants are likely to be case-specific. But for careful identification of the appropriate controlling determinants within each dimension, a firm runs the risk of trying to focus a factory by controlling arbitrary variables that may have no effect, or unintended effects, on factory performance.

Factory-level decisions that firms make along the focusing dimensions will affect the demands placed on the routines of production lines, and may determine the scope of the task of these lines. For instance, a decision to offer three rather than two types of engine on an automobile may increase the demand on the drive-train lines of an assembly plant through additional material, information, and coordination. The exact manner in which dimensional variations at the higher levels affect the demands on a production line remains an open research issue. We attempt to gain insight into this issue by examining the case of one focused factory.

The discussion of routines in this subsection of the paper provides the first element of the model that we use in this empirical study of production line focus. We have highlighted the role of self-sustaining organizational routines in achieving the production line skill of a focused factory, and have stressed the need to limit variation along its multiple focusing dimensions. We now look at the second element of the model: absorptive capacity for adaptation.

2.2 Absorptive Capacity for Adaptation

We have argued that focused factories achieve highly effective activities by creating, using and reinforcing a limited set of self-sustaining routines in their production lines. Over time, in a relatively stable environment, this can result in outstanding performance. Earlier, we noted that all or most focused factories eventually will face a need to change their activities. The self-sustaining nature of routine operations may make it difficult for organizational units to change their activities to adapt to new manufacturing requirements. That is, a factory or production line usually will have little difficulty conforming to prevailing routines, but may find it challenging to depart from them. The difficulties arise because members of a unit need to learn new systems of coordinating, add new skills to their repertoires, and reconcile their cost-benefit expectations (Nelson and Winter, 1982).

The degree of this difficulty often depends on how related the new task is to the old task of the unit. Responding to a new task may require unlearning, learning and, responding in a new physical or knowledge domain. This requires an ability to evaluate and utilize new knowledge, which Cohen and Levinthal (1990) call absorptive capacity.

While researchers have not used the concept of absorptive capacity at the level of the production line before, studies at hierarchical levels both below and above production lines do use the concept. Cohen and Levinthal (1990) base their argument on the literature in individual learning, and establish absorptive capacity largely as a function of prior related knowledge. Specific to manufacturing firms, Abernathy (1978) and Rosenberg (1982) have noted that direct manufacturing experience helps a firm to recognize and utilize new information relevant to a specific product-market. We believe that this argument is also applicable at the production line level.

Absorptive capacity of a production line develops cumulatively, through transfer of knowledge within the members of a line and through the interface of the line with its environment. This environment may include other lines and functions within the factory, as well as external agents such as parts suppliers. There may, however, be a trade-off between the amount of knowledge sharing within the members of a line, and the amount of knowledge-diversity across them. This manifests in a trade-off between the efficiency of internal communication within the line, which is the inward component of absorptive capacity, and the ability of the line to assimilate and exploit information from elsewhere, which is the outward component of absorptive capacity. Focusing a production line is likely to stress the inward component at the expense of the outward one. This is an extension of Arrow's (1974) argument that the efficiency of an internal communication process is one of the reasons firms are an economically attractive form of organization.

A production line may retain absorptive capacity as a by-product of routine activity if the new knowledge domain is closely related to the current one. Indeed, Nelson and Winter (1982) note that the expected future behavior of firms resembles the behavior that the firms would achieve if they simply followed their past routines. While the notion of resemblance is ambiguous, the concept suggests that for two production lines focused on similar tasks and having similar absorptive capacities, the one with less difference between old and new tasks will perform better.

For new domains of knowledge that differ markedly from current domains, production lines must develop new absorptive capacity to be successful. However, absorptive capacity is path-dependent, that is, it tends to be cumulative and draws on past expectations. A low initial investment in absorptive capacity diminishes the attractiveness of investing in it in subsequent periods, and production line operations may be trapped within a particular knowledge domain. Therefore, pursuit of a narrow focus in one period may inhibit the incentive to invest in absorptive capacity unrelated to the initial focus in subsequent periods. Thus, focus may be a condition under which development of unrelated absorptive capacity may appear less attractive to a firm. Even if new investment does appear as an alternative, managers of a focused factory may be reluctant to give up current gains from focus to allow its people and systems the diversity to gain absorptive capacity.

2.3 Propositions

In summary, we have defined production line focus as repeated executions of a limited number of routines. Further, highly focused factories will tend to have routines that are consistent with the specific skills that the factory requires in its particular competitive environment. Management can limit the set of skills that a factory requires and the set of routines that a production line executes by limiting the operating range of the relevant controlling determinants along the focusing dimensions. A change of focus requires that production lines learn new skills, while the ability of a production line to learn new skills depends on the absorptive capacity of the line for the specific change. Accordingly, we suggest the following propositions.

> **Proposition 1**: The performance of focused production lines will decline after the lines adopt new routines that are outside the scope of the absorptive capacity developed through the execution of their prior manufacturing tasks.
>
> **Proposition 2**: The performance of focused production lines will not decline after the lines adopt new routines that are within the scope of the absorptive capacity developed through the execution of their prior manufacturing tasks.

These propositions are the basis of hypotheses that we test using data from the Hartselle focused factory. The next section describes the methodology and empirical context of our study.

3. Research Methodology and Empirical Site

In this section we discuss our adoption of a single-site field-study as the appropriate methodology to reach the research objectives we are pursuing. Then, we discuss the evolution of focus at the particular site where we conduct the study.

3.1 Single-Site Field Study

Empirical research on focused manufacturing faces problems with the basic tenets of definition as prescribed for socio-technical research (Lachenmeyer, 1971). These difficulties mirror those faced in similar efforts in other fields, as discussed by social-science scholars such as Verba (1976) and Campbell (1975). Such difficulties have led researchers in several fields to recognize the importance of single cases as a desirable research method in such situations (Lasswell 1968, Naroll 1962, Becker 1970, Russet 1971).

An interpretive case perspective is appropriate for our study due to the following reasons. First, context dependence of an object or behavior in large sample studies may result in inferences that are either simplistic or tautological (Campbell, 1975; Cronbach, 1975). For Operations Management research, Hill, Scudder, and, Haugen (1987) note such limitations of the large sample perspective. Second, most large sample research tends to emphasize reliability by increasing sample size without examining the effect on validity, while high reliability may be associated with zero validity (Emory, 1985, pp. 94-98). The lack of a universal, measurable definition of focus makes this roadblock unavoidable. Interpretive research, on the other hand, can successfully investigate specific phenomenon through in-depth, but limited-scope studies. Finally, large sample research based on perception of object reality assumes uniformity and reliability of secondary source knowledge. The practitioner literature highlights the potential fallacy of that assumption regarding focused manufacturing (e.g., Harmon 1992, Rommel et al. 1995). Consequently, primary source methods are appropriate in the study of factory focus, consistent with long-standing views concerning the relevance of single-site field studies (Donham 1922; Lijphart 1971, 1975).

We view this case study as a theory testing case study, following Yin's (1984) typology, since this research follows the traditional model of generating its propositions from theory rather than from evidence. The critical requirement for a single-site study is to formulate the explanation for the case in terms of general rather than idiographic variables (Eckstein 1975, George 1979). Further, because our units of analysis are production lines within a factory, the availability of several units within one case serves the research objective by allowing us to study several outcomes within a constrained case.

We followed guidelines for theoretical site-selection by George (1979) and Eisenhardt (1989). Through a survey of the literature and subsequent dialogue with company management through meetings and unstructured interviews, we selected the flagship factory of the Copeland Corporation at Hartselle, Alabama as the study site. We selected the site due to its experience with a successful focus and because it underwent a subsequent defocusing. We collected information on the Copeland Hartselle factory from several sources including: HBS Case # 9-686-088; HBS Film # 9-887-527; Focus Revisited, by Dean M. Ruwe, Copeland Document, 1991; Copeland internal reports, documents, and archives; Copeland public documents; and, interviews with several Copeland managers over the period 1991 to 1994.

3.2 Evolution of Focus at Copeland Hartselle

In 1979, Copeland established its 256,000 square feet flagship factory at Hartselle, Alabama at a cost of $30 million to manufacture one million units annually of a new, high-efficiency, CR model refrigerant compressor. The company decided to serve the market with a few compressor models assembled from multiple combinations of a few parts to be produced in large batch sizes with the minimum of factory complexity.

3.2.1 Initial Focus: 1979-1985

Copeland divided the facility into two areas, machining and assembly. Machining carried out various metal removal processes such as milling, turning, drilling, and grinding. The machine shop was the center of focus in its consumption of planning efforts and investment. It had seven machining lines, which we designate as ML1 (Machining Line 1) through ML7. The manufacturing task of this shop was to excel in high volume, high precision machining of a narrow mix of components to attain the world's best cost position. The plant implemented this focus successfully and the machine shop became a showpiece for the company in the early nineteen-eighties.

The assembly lines put together various machined and purchased parts to form a complete compressor. The operations comprise several fastening, fitting, welding, and brazing processes. Out of a total of eight assembly lines, four are for sub-assemblies, which we designate as AL1 (Assembly Line 1), AL2, AL3, and AL4. The other four are main assembly lines, which we designate as AL5, AL6, AL7 and AL8. The manufacturing task of the assembly shop was to build end-product variety through multiple combinations of the relatively few basic components. Accordingly, the assembly lines had much lower set-up times and many more manual operations compared to the machine shop lines.

Hartselle, in its initial years, was a tightly focused factory in terms of the focus map of our conceptual model in Figure 1. The factory, and in particular, the machine shop which was the center of focus, had positions close to the center of the figure along all dimensions. The plant produced a narrow part mix. On the process dimension, Hartselle chose not to manufacture several parts that required a manufacturing technology other than high precision machining. The factory produced its machined components only in high volumes. The factory also had tight focus along the customer and geographic dimensions. It served only a few market niches for compressors, namely, domestic air-conditioning, and commercial refrigeration, mostly within the continental United States. It also developed a limited set of suppliers for its stable set of parts and material requirements. We will depict Hartselle through its focus map after we describe the defocusing of the factory.

Copeland management also tailored the infrastructural system of the factory to carry out the focused task (See Hayes and Wheelwright,1984, for a discussion of structural versus infrastructural systems). Product design modifications made parts amenable to high volume production. The focus on long production runs of high volume, high precision components on dedicated machines also gave rise to specific batching and scheduling guidelines, accompanying off-line quality assurance systems, and specific procedures of other infrastructural elements like maintenance and material handling.

The advantages of Hartselle's initial focus stem from pursuing scale and scope of production, as well as complexity reduction. Relevant benefits due to the scale of production include using scale as a key mechanism in achieving a focus on cost reduction, taking advantage of declining average costs on the high-volume end of a volume-split, and pursuit of declining average costs by tailoring the infrastructure to focus it on the machining processes. Next, focusing on limited operating ranges including a limited number of products reduced the chances of diseconomies of scope and scale. Finally, benefits due to complexity reduction include reducing complexity-driven coordination costs by reducing the environmental and technological complexity of the factory, and facilitating tailoring by reducing the organizational complexity of the factory. With the focused factory fully operating, Copeland was transformed from an industry follower to the undisputed industry leader.

The risks of the initial focus at Hartselle include: avoiding tasks other than cost reduction through the pursuit of scale; experiencing diseconomies of scale due to continued focus on high-volume beyond a certain limit; potential diseconomies of scope if the plant was required to proliferate its product portfolio; curtailing the ability to manage complexity due to the insistence on reducing it; and, a potential lapse of managerial discipline to avoid profitable markets, customers, or geographic regions in order to retain the focus of the factory. In 1982 and again in 1984, Hartselle went through two concentrated efforts to maintain and sharpen its focus. Through detailed studies of products, the company transferred all low volume products from Hartselle to other plants.

3.2.2 Change in Manufacturing Requirements: 1985-1991

Market pressure for broader product lines and customized modifications coupled with Copeland's aggressive marketing strategy gradually necessitated that the product line of Hartselle be defocused. This study covers a period between 1985 and 1991, when the machined components proliferated little, but the end products proliferated considerably. Minor model changes also occurred through the introduction of a new product, the CR4. Within the Copeland system, product variety is measured by bills of material (BOM) at two levels, the '13-digit CR,' which is the basic or the core compressor, and the '17-digit

CR,' which is the differentiated compressor with peripherals such as mountings, fittings, and electricals. The '13-digit' and '17-digit' are nomenclature systems comprising alphanumeric codes. Figures 2.1 and 2.2 show the product proliferation on a monthly basis of the 13-digit core basic compressor, and the 17-digit differentiated product, respectively, for the years 1985 through 1991. Although data concerning the period prior to 1985 are not available. Copeland managers indicated that the proliferation began shortly before 1985.

********** **Figure 2.1 and Figure 2.2 about here** **********

Figures 2.1 and 2.2 illustrate the change in the number of products, which is a key dimension of focus. Changes occurred along other determinants of focus as well. For example, Table 3 compares the quantities and the number of final product models sold along the "customer type" focusing dimension in 1986 versus 1991. While detailed data similar to those pertaining to number of products and customer type are not available for each focusing dimension, discussions with management suggest the a focus map as shown in Figure 3 depicts the evolution of focus at Hartselle over a ten year period. Defocusing activities along the dimensions include product proliferation, modification in process technology, expansion of customer base as well as geographical reach, heterogeneity of production volume, and broadening of the supplier base. This multidimensional perspective on factory focus is important because we found that management's initial perception of focus tended to concentrate on the product dimension, consistent with much of the writing in the literature about focus. This emphasis on a single dimension increased the chance that unexpected problems would arise during the defocusing period.

********** **Table 3 and Figure 3 about here** **********

To summarize, the initial meetings with the corporate and plant management showed that the site suited the study, due to its experience with an initial focus and a subsequent defocus. The presence of fifteen production lines in two different areas, machining and assembly, provide an opportunity to look for robust inferences.

4. Research Hypotheses

In this section, we define operational measures for production line performance criteria and production line focus, and propose empirical hypotheses.

4.1 Production Line Performance Criteria

We operationalize production line performance in terms of two measures, including labor productivity and conformance quality. The traditional measurement of labor productivity reflects the efficiency of the transformation process occurring at a production line. A transformation process is a collection of its various routines. Changes in the execution of the transformation process may result in new or modified routines that are outside the repertoire of routines that a production line can execute without conscious overview. Change can, therefore, slow the pace of execution of routines at a production line. Further, change can also lead to a mismatch between the task information needs and the information processing abilities of the line. A production line may absorb the additional task information needs by under-utilizing its resources, including labor resources (Galbraith 1977). Usage of more labor resources to perform a task would lower the efficiency of labor utilization. Therefore, labor productivity reflects the efficiency with which members of a line execute their routines.

The second measure of production line performance, conformance quality, reflects the degree of conformance of the executed routines to the designed ones. When a change in task stretches the production routines, the mechanisms that control the execution of the routines may not allow the pace to slow down to adapt. Examples include production quotas and automatic conveyors. The result may be that the task or the process to which the routines belong will not conform to its design specifications. The effect of non-conforming routines of the transformation process may be a less than desired quality of the process itself. A production line may also absorb a mismatch between task information needs and information processing capabilities by not meeting the additional task need fully, and thereby, by not conforming to the design of the task. An indicator of the quality of the process is the conformance quality of the parts produced by the process.

4.2 Production Line Focus Measures

We also operationalize production line focus in terms of two measures, including number of part numbers and heterogeneity of production volumes. Production line focus is a hierarchical consequence of factory focus. As we noted in Section 2. there usually is not a single way to derive variables at the production line level corresponding to every controlling determinant at the factory level for every firm in every industry. We use an approach that we believe is applicable to many discrete manufacturing environments.

Our first production line focus measure is the number of distinct part-numbers. Limiting the number of parts with distinct part-numbers at a line is one way to limit the demands placed on the production line. While the number of products at the factory level provides little information about the extent to which these products place different demands on the system, the number of parts on a production line may capture much more adequately the variations placed on the line. A production line within a discrete manufacturing facility usually possesses specific processing capabilities to manufacture parts within given ranges of specified design parameters. A new part on a given line often indicates change of a rather limited nature, mostly on values of design dimensions and processing parameters. For example, on a gear-shaping line producing two gears, the addition of a third part-number will typically indicate another gear that goes through the same shaping operations in the same sequence as the other two, only with changes in process parameter values.

Our second production line focus measure is the heterogeneity of production volumes. Limiting the heterogeneity of volumes is another way to limit the demands placed on a production line. A production line can produce the same number of parts in large, medium, or small volumes. Uniformity of batch sizes may help a production line adopt the economically and technologically appropriate elements like tooling, jigs and fixtures, material handling systems, production planning and quality control systems, and work routines. Heterogeneity of volumes stretches the designed capabilities of these elements. Two compressor manufacturing plants of Copeland Corporation at Alabama and North Carolina exemplify successful focusing of these elements on large only and small only batches respectively (March and Garvin 1986).

We now turn to Table 4. The second column of the table lists several controlling determinants for each dimension of focus that we listed in Table 1. The third column of Table 4 then lists, for each controlling determinant, production line level implications for the two measures of production line focus.

********** **Table 4 about here** **********

Our intent in the above discussion is to demonstrate that part mix and volume heterogeneity at the production line level associate with variations of many controlling determinants of focus at the factory level. There may be other variables to control in limiting the demands at the production line level. A new technology may imply redistribution of line level direct and indirect labor, for example. Changes in supplier relationships can alter the level of inventories held at production lines. Many other forms of change in parts, labor, and technology occur at the production line level in different cases. Nonetheless, although our list is not exhaustive, the measures apply to many manufacturing situations. We believe that the measures are appropriate for this study and many other cases.

4.3 Research Hypotheses

We propose three sets of hypotheses that link change of focused task with performance of the production lines, addressing machining lines, assembly lines, and linkages between lines. The focused tasks of the machining and assembly lines differ in design, in ways that affect their absorptive capacity relative to the new tasks that the lines undertook during the study period. Copeland designed the machining lines with the intent of excelling in producing a narrow part mix in large volumes. We propose that a changed task involving either a greater number of parts or smaller volumes has a detrimental impact on the performance of the line. While the overall set of components processed by a line did not change, the number of types of components within that set processed in a given month did. In terms of the volumes in which they processed the parts, the machining lines experienced a gradually increasing mix of large and small batch sizes over the period of the study, thus increasing the heterogeneity of part volumes. Therefore, the monthly performance of a machining line may decline as its focus weakens, as the subset of parts processed in a month increases and as the heterogeneity of monthly part-volumes increases. Based on these arguments, we propose the following hypotheses for each machining line:

> H1A: Labor productivity of each machining line declines as the product mix processed by the line broadens.
>
> H1B: Conformance quality of each machining line declines as the product mix processed by the line broadens.
>
> H1C: Labor productivity of each machining line declines as the heterogeneity of volumes of the components produced at the line increases.
>
> H1D: Conformance quality of each machining line declines as the heterogeneity of volumes of the components produced at the line increases.

Copeland designed the assembly and sub-assembly lines with the intent of producing multiple products through multiple combinations of a few components. Thus, the firm expected the assembly lines to produce high product-variety through lower set-up times and manual operations. Over time, product-variety increased and the volumes in which products were assembled decreased. Given that a high product variety was not a new task for the assembly lines, but smaller volume was a new task, we expect that the performance of the assembly lines declines with an increase in the heterogeneity of product volumes, but does not change with a change in the product mix. Formally, we propose the following hypotheses for each assembly line.

> H2A: Labor productivity of each assembly line declines as the heterogeneity of volumes of the products assembled at the line increases.
>
> H2B: Conformance quality of each assembly line declines as the heterogeneity of volumes of the products assembled at the line increases.

H2C: Labor productivity of each assembly line remains unchanged as the product mix assembled at the line broadens.

H2D: Conformance quality of each assembly line remains unchanged as the product mix assembled at the line broadens.

The final hypotheses address linkages between production lines. Production lines of a factory often interrelate through a common flow of material and information. Following Perrow (1984), these production lines are subsystems of the factory. Consequently, the sequence, timing, and magnitude of manufacturing activities taking place within a subsystem may be affected by the interaction of that subsystem with other subsystems. The change of task at a line, therefore, may be either an explicit activity of a line or an indirect result of an explicit change at an interrelated line. An explicit change in the product-mix of the assembly lines may lead to an indirect change in the demands on the machining lines, due to greater complexity and variation in component demand. Such an effect is of great interest, because management may mistakenly act as if the task of the machining lines has not changed, since their sets of components have remained unchanged.

Further, in a focused factory such as Hartselle, the thrust in tailoring is on the configuration of the infrastructural elements to make them consistent with each other and with a system-level deliverable, following Skinner's (1974) prescription. The span of these elements remain system-wide, across the factory. The production lines of the factory, subject to a common material and information flow and joined by the same infrastructure, may constitute a richly joined system (Ashby 1960), or a systemic system (Simon 1969). The interesting property of such systems is that interaction between subsystems is stronger than interactions within each subsystem. We take a conservative view and propose the following hypotheses that address only productivity variables, due to data limitations.

H3A: Labor productivity of each machining line declines as the product mix at its corresponding downstream assembly line broadens.

H3B: Labor productivity of each assembly line remains unchanged as the product-mix at its corresponding downstream assembly line broadens.

Table 5 summarizes the conceptual, and operational dependent and independent variables, of each hypothesis.

********** **Table 5 about here** **********

In conclusion, this section presents three sets of hypotheses. The first two sets propose that a change in the task of a production line leads to a decline in the performance of the line when the line lacks absorptive capacity for the task, but not otherwise. The first hypotheses address the machining lines, while the second set addresses the assembly lines. We present separate sets of hypotheses for the machining and assembly lines because we expect their absorptive capacities to differ relative to the changes that they undertook. The third set of hypotheses proposes that indirect changes occurring at interrelated downstream production lines may affect the performance of an upstream production. For each set of hypotheses, the generalizable variables are specific to the case in their operationalization. In the next section, we describe the methodology and the measurement of the variables to test the hypotheses at the site, and then present the results of the empirical tests.

5. Empirical Methods for Testing the Hypotheses

Empirically testing the hypotheses involves examining line-specific relationships across several production lines between the variables over time. Lindsey (1993, pp. 3-16) refers to the methodology as testing with longitudinal data because: i) the analysis measures the same variable on the same observational unit more than once, such as our measurement of the labor productivity variable for the production line observational unit; and, ii) the study examines more than one observational unit: specifically, seven machining lines and eight assembly lines, preventing the formation of a simple time series. Using this approach to testing with longitudinal data, one can make valid inferences by borrowing strengths across units of analysis (Diggle, Liang, and Zeger 1994, pp. 2-22). That is, the basis for substantive conclusions is the consistency of a pattern across these units, which in our case are the production lines. Consequently, inferences from longitudinal studies can be more robust to model assumptions than those from time series data. Multivariate normal distributions with an unspecified covariance structure can successfully model such instances.

5.1 Model

A general linear model for T repeated observations at each of N units of analysis is given by,

$Y \sim \text{MVN}(M, I_N \times \Sigma)$

where, Y is the $N \times T$ matrix of observations

M is the $N \times T$ matrix of the means μ_{it} of each variable y_{it}

I_N is the identity matrix

Σ is the $T \times T$ covariance matrix of the observations

MVN represents multivariate normal distribution function

for, $i = 1, \ldots\ldots\ldots, N$

and, $t = 1, \ldots\ldots\ldots, T.$

Our sets of hypotheses guide us in selecting the appropriate model from the several possible specific classes of the general model. The hypotheses in this study are similar to cases in which different economic and demographic background factors imply that parameters may be different for different units. Variable coefficient models of the following form are appropriate in such cases (Kuh 1963, Swamy 1970):

$$y_{it} = A_i + \sum_k B_{ki} x_{kit} + e_{it} \quad (i = 1, \ldots, N;\ t = 1, \ldots, T;\ k = 1, \ldots, K)$$

where, A, B, and e indicate the intercept, slope and the error term of the regression of the observations on independent variables x, and K is the number of independent variables.

We estimate the parameters using the scale-independent correlation coefficients of separate least-square regressions for each unit. When regression coefficients are invariant over time, but varying from one unit to another, and one is interested in predicting the individual component B_i, Swamy (1970, 1971) has shown that the best linear unbiased predictor, conditional on given B_i, is the least squares estimator. The conditions of time-invariance and unit-variance also make the estimation of the parameters equivalent to postulating a separate regression for each unit (Hsaio 1986, pp. 128-153).

Further, our intent in the statistical analyses is to formulate an explanation in terms of general variables. Seeking direct relationships serves such studies well, since potential generalizability of relationships are of prime concern (George, 1979). This is particularly true in this case since the state of the understanding of focused manufacturing in the literature commits conceptual violations of basic tenets of definition (Lachenmeyer, 1971). Several researchers note that using multiple regression under such conditions, for example, may lead to wrong conclusions about hypotheses (Ryan 1960, Scheffe 1953, Selvin and Stuart 1966). Further, multivariate models with random effects are difficult to construct with validity since there may be many unknown characteristics affecting a performance variable like labor productivity. Accordingly, we employ ordinary least square regression models. For each hypothesis, we propose a linear relationship between the independent variable x and the dependent variable y separately at each line, i.e.,

$$y_t = A + Bx_t + e_t \quad \text{(for the t-th of T observations)},$$

where e_t is the residual term of the regression, and A and B are the least-square coefficients estimated as,

$$A = \Sigma y_t/T - B\,\Sigma x_t/T$$

$$B = \Sigma(x_t - \Sigma x_t/T)(y_t - \Sigma y_t/T) \,/\, \Sigma(x_t - \Sigma x_t/T)^2$$

The magnitude of the variables at the site can vary widely across production lines, however. For example, labor productivity of a line may depend on the nominal labor hours required to produce a unit of product, and the nominal amount may vary widely from line to line since different lines make different products. Therefore, we use the scale-independent correlation coefficient rather than the regression slope for better comparability. By expressing the variables in the mean deviation form, it can be shown (Fox 1984, pp. 18-21) that the correlation coefficient of the ordinary least square regression is equivalent to the Pearson correlation coefficient between two random variables, except that unlike the latter, it changes with scale.

Next, we discuss the potential sources of bias in the model. Economic data often violate the typical assumption made in data generated from controlled experiments that the dependent variable is generated by a parametric probability distribution function identical for all individuals at all times (Hsaio, 1986, pp. 5-8). Ignoring parameter heterogeneity among units can lead to inconsistent or meaningless pooled estimates of parameters. This study avoids the problem of heterogeneity bias by using subject-specific rather than pooled estimates of parameters. Another frequently observed source of bias, known as selection bias, is that the sample may not be drawn randomly from the population. That is, the sample selection procedure introduces correlation between right-hand side variables and the error term, which leads to an upward or downward bias in the regression line (Hausman and Wise 1977, Heckman 1976, 1979). This study avoids the selection bias since it examines all available units of analysis, rather than a sample of them. Finally, using a ratio, such as labor productivity or fraction non-conforming, rather than an absolute quantity such as output volume as a dependent variable, can avoid the problem of having a common time trend between observations of dependent and independent variables, as observed by Davidson and MacKinnon (1993, p. 670-671) and Brush and Karnani (1996).

5.2 Data and Measurement of Variables

This case study is consistent with several others (Sutton and Callahan 1987, Mintzberg and McHugh 1985, Eisenhardt and Bourgeois 1988) in its seeking both quantitative and qualitative evidence. We retrieved the quantitative data from company records. Table 6 summarizes the measurement and data sources of the variables that we used to test hypotheses sets H1 and H2.

********** **Table 6 about here** **********

We first address the production line focus variables. Consistent with our discussion of the variables in section 4, we measure the part-mix at a production line through the number of parts. To collect data on part mix, we tracked the chronological production of each of 1,300 parts, sub-assemblies, and assemblies produced. For each item, the data comprise monthly production volume for a 48 month time-period between 1986 and 1990. Since each component, sub-assembly, or, assembly has its own unique part-number, the appropriate measure of part-mix at a line in a given month is the number of part numbers processed at the line during that month.

To measure volume heterogeneity, the other focusing variable, we consider parts with the same part number as homogeneous, and parts with different part numbers as heterogeneous. At each production line, we aggregate the production volumes of each homogeneous part. We then measure the dispersion between the several aggregate monthly volumes corresponding to the several part numbers at a line using the variance of these monthly volumes as a measure of volume diversity. For n variables $x_1, \ldots\ldots, x_n$, this measure is defined as, Variance = $(\Sigma(x_i - \Sigma x_i /n)^2)/n$ for all $i = 1, \ldots\ldots, n$. A higher variance indicates greater heterogeneity of volumes. However, the monthly variance may not capture the entire heterogeneity that essentially occurs on a weekly or daily basis, depending on the line. Unfortunately, the production data are available only on a monthly basis. Therefore, we use a second measure of volume heterogeneity, the Hirschman-Herfindahl Index (HHI), as an additional measure of volume diversity[2]. For n variables $x_1, \ldots\ldots, x_n$, the index is defined as, HHI = $\Sigma x_i^2/(\Sigma x_i)^2$, for all $i = 1, \ldots.., n$. For a given number of parts on a production line, a higher HHI indicates a greater heterogeneity of volume, and thereby a greater deviation from the focus on high volumes. Between the two measures we employ, variance is a measure of dispersion, while HHI is a measure of dominance. However, monthly data is only an aggregation of the pattern of the dominance or dispersion that occurs within shorter time-periods. Consequently, while we expect volume heterogeneity to be a key variable in our analysis, we have no a priori preference between the variance and the HHI measures of heterogeneity.

We next address the production line performance variables. We measure the first of the two performance variables, labor productivity, through labor hours per unit produced. Higher labor-hours per unit indicate a lower labor productivity. While unit production data is available for each part number, the company aggregates labor-hour data by several cost centers of the factory, rather than by part number. Using the production lines of the factory as units of analysis mitigates the potential problem of mismatching data collection levels, however, because each production line is also a cost center. Further, the several part numbers processed at a cost center are always from the same part family. Consequently, we can aggregate the volumes in which a cost center processes each of the several part numbers to measure the output of the line. Accordingly, we use the monthly aggregate volume as the denominator and the monthly labor hours worked, retrieved from company records, as the numerator in our measure of labor hours per unit. The machining cost centers collect direct and indirect labor hour data separately because the indirect labor requirements are generally substantial, that is, of the same order of magnitude as direct labor. Assembly cost centers, however, have little or no indirect labor because the indirect labor requirement for the assembly processes is negligible. Accordingly, we use productivity of direct and/or indirect labor as appropriate for each line. Also, for lines where direct labor standards have changed over the time period of concern, we use the productivity of standardized direct labor as a measure.

For the second performance variable, conformance quality, we use scrap treatment labor hours per unit of good product as an indirect measure. Data on actual quality performance are too limited to be useful. Therefore, we measure conformance quality through this indirect variable. Our linking the costs of quality related activities and conformance quality is consistent with Juran's (1979) discussion of internal failure cost as a component of the costs of quality. Defective parts contribute to the generation of more scrap in two ways. First, the defective pieces, if not salvageable, contribute directly to scrap. Secondly, the need to produce a replacement generates more scrap material. Thus, a higher proportion of defective parts will result in higher scrap treatment hours per unit of good product. The labor hour data for this activity are available for a 24 month period. Further, the concerned cost center collects these data for the factory as a whole rather than for each line.

Testing hypotheses H3A and H3B requires examining productivity variables that we measure for each machining line from the data listed above. The analysis also requires measuring proliferation variables at two levels: i) the assembly shop lines, compressors with peripherals such as fittings, mountings, tubes, and electrical components; and, ii) the machine shop lines, core compressors without peripherals, as we explained in section 3. Since each compressor, with or without peripherals, has its own bill of material, we measure proliferation through the number of bills of material of compressors at the two levels, consistent with the measurement of part-mix at production lines.

Subsequently, we conducted unstructured interviews with managers, supervisors, and manufacturing support staff to verify our model, and to learn more about the implications of the empirical results. By their nature, unstructured interviews do not use a standardized instrument.

In the next section, we present and discuss the results of testing the hypotheses in the order we proposed them.

5.3 Hypotheses Testing: Results And Discussion

Two tables summarize the results. Table 7 lists the results of testing each individual hypothesis, including a brief description of each result. We report the results of testing hypotheses set H1 and hypotheses H2A, H2B, and H3A, denoting whether the study supports or rejects each hypothesis. For the three hypotheses that we formulated using the null hypothesis format, namely, H2C, H2D, and H3B, we report the results of testing by denoting whether or not the study rejects a hypothesis. Table 8 summarizes the results of testing these three sets of hypotheses, indicating the impact of defocusing on production line performance for all tested combinations of operational variables.

************ Table 7 and Table 8 about here ************

5.3.1 Results for H1 and H2

Two tables report more detailed results for H1 and H2. Table 9 presents results of the labor productivity analysis. We summarize the results of Table 9 in Tables 9A and 9B. For each independent variable, Table 9A lists the number of coefficients in Table 9 with positive and negative signs at different levels of significance grouped into the two shops, machining and assembly. Table 9B shows how each dependent variable on each line relates to part-mix breadth and volume heterogeneity. Table 10 reports the results of the conformance quality analysis. For each independent variable, Table 10A lists the number of coefficients in Table 10 with positive and negative signs at different levels of significance grouped into the two shops. machining and assembly. We use these tables to test the validity of the hypotheses. Then, we discuss all productivity results , followed by all conformance quality results.

********** **Table 9 and Table 10 about here** **********

The study does not support hypothesis H1A, that labor productivity at each machining line declines as the part-mix breadth of the parts processed by the line increases. Row 1a of Table 9A shows that thirteen of the seventeen coefficients are positive, as expected, suggesting that labor hours per unit increases with defocusing. However, seven of the coefficients are insignificant. Of the remaining six significant positive coefficients, two involve indirect labor hours, which are not the major fractions of the labor input to a component. Another one is weakly positive. While the other three coefficients are positive and significant, Table 9B shows that they all belong to a single machining line, namely, ML2. Also, four coefficients are negative including two significant ones. Thus, there is no convincing support of the hypothesis, and part-mix breadth does not appear to be a significant factor in explaining labor hour performance of machining lines, except at ML2. We discuss the implications of this unsupported hypothesis below.

The study partially supports hypothesis H1B, that conformance quality at each machining line declines as the part-mix breadth of parts processed at the line increases. Row 1a of Table 10A shows that out of the six coefficients, three are positive and significant at the 90% level or greater. Thus, scrap treatment often increases with defocusing. Further, unlike the productivity variables, each coefficient relating to conformance quality represents a separate line. Also, there are no significant negative coefficients. Therefore, for three of the six machining lines, the relationship between increasing machine line part-mix breadth and the variable representing internal failure cost of the factory is detrimental, and significant. The other three do not show a performance-enhancing relationship between these variables. Therefore, the hypothesis is supported at half the lines and not contradicted at any.

The study strongly supports hypothesis H1C, that labor productivity of each machining line declines as the heterogeneity of volumes of parts processed at the line increases. Row 1b of Table 9A shows that of the seventeen coefficients, eight are positive and significant at the 90% level, of which six are significant at the 95% level. Next, row 1c of Table 9A shows that of the seventeen coefficients, seven are positive and significant at the 90% level, of which six are significant at the 99% level. Also, no contradictory results arise between the coefficients derived from the two independent variables. Further, Table 9B shows that these positive and significant coefficients are distributed across five of the seven lines. Table 9B also shows that the negative coefficients, including the only one that is significant, mostly belong to two lines, ML6 and ML7. Thus, there is strong support for the hypothesis, while these two lines stand out as exceptions to this generally detrimental effect.

The study partially supports hypothesis H1D, that conformance quality at each machining line declines as the heterogeneity of volume of parts processed at the line increases. Row 1b of Table 10A shows that of the six coefficients, all are positive, with two of them significant at the 90% level. Row 1c of Table 10A shows that of the six coefficients, five are positive, with three of them significant at the 90% level. Also, the first column of Table 10 shows that significant positive variables are distributed across four of the six lines, with another line showing positive although insignificant coefficients. ML6 stands out as an exception to this generally detrimental effect with one significant negative coefficient, and another insignificant positive coefficient. Therefore, the analysis weakly supports the hypothesis, with the contradictory exception of ML6.

The study strongly supports hypothesis H2A, that labor productivity of each assembly line declines as the heterogeneity of volume of the parts assembled at the line increases. Row 2b of Table 9A shows that of the nine coefficients, six are positive with three of them significant at the 99% level. Row 2c of Table 9A shows that of the nine coefficients, six are positive with five of them significant at the 90% level. Also, there is no contradictory result between the coefficients coming from the two independent variables. Further, Table 9B shows that these positive and significant coefficients distribute across five of the seven lines. Table 9B also shows that the negative coefficients, including the only one that is significant, mostly belong to two lines, AL6 and AL7. Thus, there is strong support for the hypothesis, while these two lines stand out as exceptions to this generally detrimental effect.

The study partially supports hypothesis H2B, that conformance quality at each assembly line declines as the heterogeneity of volume of parts processed at the line increases. Row 2b of Table 10A shows that of the four coefficients, three are positive, with one of them significant at the 90% level. Row 2c of Table 10A shows that of the four coefficients, all four are positive, with three of them significant at the 90% level. Also, there is no contradictory result between the coefficients derived from the two independent variables. Further, the last two columns of Table 10 show that significant positive coefficients distribute across all four lines.

The study fails to reject null hypothesis H2C, that labor productivity of each assembly line remains unaffected as the part-mix breadth of parts assembled at the line increases. Row 2a of Table 9A shows that of the nine coefficients, four are positive and five are negative. At the 95% level, there are two positive coefficients and one negative coefficient, and at the 99% level, there is no positive coefficient, but one negative coefficient. Further, Table 9B shows that five out of the seven lines do not show any detrimental relationship between direct labor productivity and part-mix breadth. Also, Table 9B shows that of the negative coefficients, two belong to one line, namely, AL4.

The study rejects null hypothesis H2D that conformance quality of each assembly line remains unaffected as the part-mix breadth of parts assembled at the line increases. Row 2a of Table 10A shows that of the four coefficients, all four are positive with three of them significant at the 90% level. Also, the first column of Table 10 shows that each positive coefficient belongs to a separate line. Therefore, there is evidence that part-mix breadth detrimentally affects conformance quality. We discuss the implications of this rejected hypothesis below.

5.3.2 Discussion of the Labor Productivity Results

One overall conclusion from the results of testing hypotheses sets H1 and H2 is that in both shops, part mix breadth has little impact on labor productivity of production lines while volume heterogeneity has a significant detrimental impact. The reasons why part mix breadth may not affect labor productivity appear to differ for the two shops. On a given line in the machine shop, while the set of parts produced usually changed from month-to-month, it did so within a given narrow superset of parts. Different parts within a superset may be transparent to the routines if their production requirements do not differ. Even if the different parts require different routines, the part-mix change may still not affect productivity if line members readily remember all routines. Two factors may assist such remembering. First, the routines may be similar and limited in number since the parts are limited in number and all come from the same family. Second, even if all parts are not produced every month, the frequency of production of each part, generally not less than once in two months, may still be high enough for the people on the lines to remember the relevant routines.

In the assembly shop, the part-mix for any given line is broader than that for a machining line. When they built the factory, the company's managers understood that the assembly lines would have to produce a variety of end-products by assembling multiple combinations of relatively few basic components, and provided the required flexibility through short changeovers and mostly manual operations. In interviews, managers stated that "Changeover is a problem in the machine shop, not in assembly." It seems that most assembly lines attained the targeted flexibility to efficiently produce a broad part-mix. That is, assembly lines became conversant with an adequate variety of routines to produce a broad and changing part mix without deterioration in labor productivity.

In contrast to part mix breadth, volume heterogeneity detrimentally affects the labor productivity of production lines in both shops. In the machine shop, while the narrow part mix did not expand, the same mix was increasingly produced in more heterogeneous volumes, that is, in a mix of large and small batches. It is obvious that partial substitution of large batches by small batches increases set up costs and therefore decreases the productivity of the indirect labor used for set up changes. More interesting is the result that volume heterogeneity negatively affects the productivity of direct labor at the machining lines. That is, volume heterogeneity represents a kind of change that stretches the routines of direct labor. It is unlikely that volume heterogeneity affects the technological processing routines, which are mostly independent of the volume in which parts are processed. Rather, it is likely that volume heterogeneity affects the routines that coordinate the execution of technological processing routines. The assembly shop demonstrates equally clearly the difference between the effects of part mix breadth and volume heterogeneity. It seems that even though most assembly lines attained the targeted flexibility to efficiently produce a broad part mix, changing requirements put a demand on assembly lines for a type of flexibility that the lines did not possess, that of adjusting to non-homogeneous production batch-sizes.

In contrast to the other machining lines, ML2 shows a significant detrimental impact of part-mix change on all its labor hour variables. However, potential explanatory factors such as set-up time, number of parts, or frequency of set-up change at ML2 are fully comparable to those at other machining lines. Discussions with engineers and supervisors indicate that the explanation may lie in the technological process itself. They say that the processes on ML2, "always had problems," and, "kept engineers busy." Therefore, a changing part-mix has a detrimental effect on labor productivity only on the line where the process is unstable. An unstable process may be indicative of the routines not having been mastered. It is possible that changes to which stable routines can respond easily may stretch less stable routines.

5.3.3 Discussion of the Conformance Quality Results

As seen above from the results of testing hypotheses H1B, H1D, H2B, and H2D, increases in part-mix breadth as well as volume heterogeneity leads to increasing internal failure costs in both shops. One interesting result is that for several production lines, labor productivity does not fall with part-mix breadth, but conformance quality does. A possible explanation is that while a broader part-mix stretches the routines at the lines, the production control mechanisms may not allow the lines to slow down. Consequently, the expected fall in performance of the stretched routines may occur in aspects relating to the quality of execution of the routines rather than the pace of completion of them. By quality of execution of a routine we mean the conformance of an executed routine to its specifications. Another interesting result is that among the machining lines, ML6, which shows a negative coefficient, that is, an adaptive ability to adjust to a changing requirement without rising conformance defects, also exhibits a non-deteriorating relationship between the increases in part-mix breadth and volume heterogeneity, and labor productivity.

Based on our field interviews we uncovered a possible reason why focus may have distorted the role of the related infrastructural function, Quality Control (QC). During the start-up years of the focused factory, the corporate QC department worked with the plant to establish quality specifications and high-volume based inspection procedures such as dedicated fixture type gauges. The task of the plant-based quality control department consisted of maintaining documents about specifications and testing methods, providing training to operators in these methods, and carrying out inspections. In the changing environment, high-volume oriented inspection procedures, while lowering inspection costs, were likely not able to assure conformance quality.

Interestingly, the company, which earned a reputation for product quality in the early days of Hartselle, did not closely examine the functional task of QC. The reason may lie in a managerial perception that, "The task of QC essentially remained the same over time." The change was considered a non-event from a quality control point of view. Such a perception may be a consequence of what management understood focus to be. First, if a focused objective of low cost through high volume dominates the design of the QC system, high-volume based inspection, rather than process quality improvement, may become the focus of QC activity. Second, if management sees focus mainly as limiting the number of machined parts, and if that number does not proliferate, they may perceive no need to change the design of the functional task of QC. We can extend this argument to tasks of other manufacturing support functions as well.

5.3.4 Results and Discussion for H3: Joined Systems

We now proceed to test hypothesis set H3. Table 11 lists the results of regressing downstream proliferation on the labor productivity of machining and assembly lines. Table 11A lists the number of coefficients in Table 11 with positive and negative signs at different levels of significance for each of the three measures of labor productivity, grouped into the two shops, machining and assembly.

********** **Table 11 about here** *********

The study strongly supports hypothesis 3A, that labor productivity of each machining line declines as the product-mix at its corresponding downstream assembly line broadens. Row 1a of Table 11A shows that of the seven coefficients between machine line direct labor and end-product proliferation, six are positive, with five of them significant at the 90% level, and three significant at the 99% level. Row 1b of Table 11A shows that of the seven coefficients between machine line indirect labor and end-product proliferation, all seven are positive, with four significant at the 90% level, and two significant at the 99% level. Finally, row 1c of Table 11A shows that of the seven coefficients between machine line standardized direct labor and end-product proliferation, all seven are positive, with four significant at the 90% level, and two significant at the 99% level. Thus, support for the hypothesis is very strong.

The study fails to reject null hypothesis H3B, that labor productivity of each assembly line remains unchanged as the product-mix at its corresponding downstream level broadens. Row 2a of Table 11A shows that of the seven coefficients between assembly line direct labor and end-product proliferation, two are positive, one of which is significant at the 90% level, and five are negative but insignificant. Rows 2b and 2c of Table 11A are not very meaningful in a longitudinal study because there are only two coefficients in each case, so that it is difficult to draw inferences. In the only case where it is relevant, namely, at AL4, end-product proliferation strongly and detrimentally affects indirect labor. This is consistent with the detrimental impact of product-mix breadth observed earlier on AL4 indirect labor productivity in testing hypothesis H2C. Overall. however, the assembly lines show little impact of end product proliferation on labor productivity, and the null hypothesis is not rejected.

Support for hypothesis H3A suggests that the inter-subsystem effects are very strong in the machining shop. One way to examine the functioning of the richly joined system of Ashby (1960) at the site is through the functioning of a system of the manufacturing infrastructure, namely, the production control system which 'joins' the production line subsystems. Within a Materials Requirements Planning (MRP) environment (Orlicky, 1975), the demand pattern for parts at an upstream line is essentially driven by the demand pattern and inventory planning decisions downstream. Hartselle embarked on a path of growth through broadening its bill-of-material base for the end-products, and geographic reach in a competitive environment requiring fast and frequent deliveries. The resulting end product build schedule would call for frequent supplies of small batches of components. Coupled with a drive to hold down the work-in-process inventory, this resulted in frequent interruptions in the very focused task of the factory to excel in long runs of its machined parts. Indeed, the volume heterogeneity that hurt labor productivity and conformance quality at machining lines, as tested earlier through hypotheses H1, may be traced to this downstream proliferation. Hypothesis 3A makes this important connection explicit and thus, demonstrates the benefits of a more insightful understanding of focus. The expected results of hypothesis H3B reaffirms the flexibility of the assembly lines previously we observed in testing hypothesis H2C.

5.4 Summary Results at the Hartselle Site

Empirical results suggest that changes in manufacturing requirements may come from various sources, and that production lines may resist an unintended change even if they have the ability to respond favorably to an intended change. We found that the lines in both shops responded differently to two types of change, parts mix and volume heterogeneity. The machining lines generally show non-deteriorating labor cost performance when the part mix changes, but we note that the changes occur within their intended sets of parts. Similarly, the assembly lines generally show non-deteriorating labor cost performance when the part-mix broadens, but we note that management intended these lines to assemble a broad part-mix. In contrast, lines in both shops, in general, exhibit a detrimental impact of increasing volume heterogeneity on labor hour performance. Therefore, increase in volume heterogeneity strongly influenced performance, but may not have been understood to do so. Managers may have focused on narrow part-mix as the key to productivity, while productivity was reduced by this other, unobserved factor.

The results also suggest that we may explain the impact of change on operational performance through the impact of changed production routines, and this impact on production routines may arise in different ways. The impact could come from reducing the pace of the production routines, as well as from lack of conformance of the executed routines to their designs. One or both kinds of the mechanisms may take place at a production line, hurting its labor productivity and conformance quality, respectively. Further, there is some evidence that the extent of mastery of the routines, as reflected by the stability of the technological process concerned, affects the pace of execution of production routines.

We also find that inter-subsystem effects in the factory are very strong. That is, the performance of a production line may be affected by changes occurring elsewhere in an interconnected production system, as well as from changes occurring at the line itself. Such indirect effects mean that managerial attempts to achieve a low-cost target may fail, even if they retain the narrow part-mix in the machine shop, the ostensible focus of the factory in realizing its low-cost target. Costs at a machining line may increase if the product-mix breadth expands at an assembly line that is connected to the machining line.

In the next section, we extend these results beyond the Hartselle site and discuss what the empirical results imply for focused manufacturing in general.

6. Implications of the Results for Manufacturing Management

The general implications drawn from this study address limits and paths to changing the manufacturing requirements of a factory. The key limiting factor we observe is that a deviation from focus may affect factory performance in unexpected ways. Issues arise in several areas, including implications for focal and complementary dimensions of manufacturing requirements and objectives, performance of connected systems, differential influence of new and existing absorptive capacity, and implications of routine stability.

Since absorptive capacity is path dependent and cumulative, changes to operations occurring in controlling determinants, performance criteria, and processing stages other than the focal ones may go largely undetected. For example, managers may rely in their decisions about a change primarily on an analysis of the change along one focal controlling determinant. Such a decision-making approach makes the implicit yet restrictive assumption that the change does not impinge on any other determinant of focus that can affect performance. Consequently, there is a risk that management of change may occur through the monitoring of an inappropriate determinant of focus that may have no effect, or even an unintended effect on performance. This is analogous to attempting to control production costs without understanding the drivers of cost (Kaplan 1984).

We recognize that managers usually attempt to consider multiple performance objectives that relate to focal dimensions. However, managers may concentrate more on the objectives that are vital to succeeding in a market than those necessary to participate in the market. Hill (1989, pp. 36-46) refers to the two types of objectives as order winners and order qualifiers, respectively. This study indicates that due to the initial relative allocation of managerial attention and the path-dependent nature of absorptive capacity, analysis of a proposed change may pay little attention to its effect on objectives other than the focal objective, which management views as the order-winner. Consequently, there is a risk that while the factory may be able to preserve its performance along the order winner dimension, poor performance along other dimensions may cause order disqualification. A dynamic environment compounds the risk, since order winner and order qualifier objectives may switch places or change drastically over time.

Our results also suggest that analysis of a change needs to consider whether the task of a production unit can change as an indirect result of a change occurring at a connected unit. Connected units may include plants within a network, 'plants-within-a-plant,' and production lines within a plant. These configurations often have specific benefits, such as greater system-wide capacity utilization with a network of flexible factories that share technological processing capabilities (Graves and Jordan 1991) and lower production costs at plants-within-plants that share overhead resources (Skinner 1974). Plant managers may have to explicitly understand and manage the trade-off between such benefits and the risk of indirect detrimental impact on performance. However, this understanding may be difficult because managers of a particular unit may not have adequate knowledge of, or control over, events taking place at another unit. Consequently, in the absence of any direct change, unit managers may mistakenly conclude that the task of their unit has not changed, while indirect changes affect the unit. Even senior managers overseeing multiple connected units often will be unfamiliar with some potential indirect effects. As a result, production unit performance may suffer due to seemingly obscure reasons.

Although some changes in manufacturing requirements cause performance problems, other changes provide paths for effective adaptation. In this study, the most effective changes required little or no new absorptive capacity relative to the traditional tasks of production lines. These changes may remain transparent to the production line routines. Transparent changes offer managers the opportunity to exploit and benefit from the change from perspectives such as marketing without harming manufacturing performance. Our results indicate that the role of focus here is to define the task envelope that the organizational memory of the production system can process routinely, and to ensure frequent enough repetitions of the production routines, so that production lines do not suffer from not remembering due to not doing.

The final implication of the results is that a line with less stable routines may be less able to adapt to changes. Therefore, the operations of a production unit may need to stabilize before the unit can accommodate changes in its manufacturing requirements. Further, even tasks known to be transitory may need adequate managerial attention, since successful response to a subsequent longer-lasting task may depend on mastery of skills required to carry out the transitory task. The result raises an additional, important issue in industries where technologies may change too rapidly for processes to stabilize. These processes may have lower tolerance for change than processes in more traditional industries, and yet, face more rapid changes. Therefore, these industries may have to pay a manufacturing penalty unless they appropriately manage process development and improvement. This issue is particularly important since the short product life cycles often found in industries such as computer and electronics manufacturing may tend to focus managerial attention more on the products than the processes.

In the next section, we draw more general conclusions about this work and discuss future research directions.

7. General Implications and Conclusions

This study has implications for the streams of literature concerning focused factories, manufacturing flexibility, organizational change, and evolutionary change. The results also point to the need for careful consideration of units of analysis.

One empirical contribution to the focused factory literature lies in establishing statistically supported relationships between determinants of focus and manufacturing performance criteria at the production line level. The decline in performance with respect to part volume heterogeneity, but not with respect to part mix breadth, highlights the importance of using appropriate metrics in studies on the effect of product variety on performance. It may explain why some empirical studies (Hayes and Clark 1985, Kekre and Srinivasan 1990, Foster and Gupta 1991) that use relatively simple measures of product variety find little correlation between variety and cost, while studies (Banker et al., 1990, Anderson 1995, MacDuffie, Sethuraman, and Fisher 1996) using more sophisticated measures of product variety find a detrimental impact of variety on performance. Further, the result that volume heterogeneity is a strong determinant of performance demonstrates the need for understanding changes in manufacturing requirement through dimensions other than the product dimension, which, as seen from the references cited above, is the most commonly researched dimension in the operations management literature. This result may also explain in part the 'something real' that prevented Milgrom and Roberts (1990) from being able to include the number of products in a cluster of complements that increase the profits of a modern manufacturing firm.

The results also contribute to the literature on manufacturing flexibility by adding and examining the concept of volume heterogeneity to the type of flexibility labeled as 'volume flexibility,' which refers to the ability of a production system to operate economically at several levels of aggregate production volume (Browne et al., 1984; Sethi and Sethi 1990; Gerwin 1993;). In a multi-product environment, volume heterogeneity can change without any change in the aggregate volume. It seems rather curious to us that that this aspect of flexibility is not explicitly mentioned in the major review articles. Further, we are unaware of other articles that systematically study it. Thus, there is a need to recognize this aspect of flexibility separately with its own description, measure, and enabling elements.

The results link manufacturing focus with research on organizational change by noting that manufacturing focus may be a condition under which development of absorptive capacity (Cohen and Levinthal 1990) unrelated to current manufacturing task appears less attractive. Absorptive capacity is path dependent. Focus may define the boundaries of the path rather narrowly through emphasis on selected determinants, objectives and processing stages, and thereby trap production units to operate in the particular knowledge-domain of their initial focus. This raises an important question: what are the principles that may guide the appropriate balance between the benefits of specializing in the current task, and the future costs of not having the absorptive capacity to adapt to tasks unrelated to the current one? More specifically, the question for manufacturing focus is of determining what the issues are in designing a manufacturing system that can focus on one task in the short-term. and can easily refocus on another task when needed.

Our results apply and extend Nelson and Winter's (1982) model of evolutionary change in a production context, and suggest that we can examine the execution of routines from two aspects that may have an impact on the performance of the routines. The impact could come from more resources being consumed to execute a routine, as well as from lack of conformance to the specified design of the routine. One or both kinds of the mechanisms may take place at a production line, hurting its labor productivity and conformance quality, respectively. The results also indicate that adaptive mechanisms that prevent the deterioration in the pace of production line routines may have some commonalties with those that prevent a deterioration in the quality of execution of these routines. We may extend similar arguments about execution of routines to contexts other than production.

The results also show some support for Nelson and Winter's (1982) theory that greater mastery of existing routines facilitates responding to new tasks. There are two implications of this for the Operations Management literature. First, for several techniques and processes of manufacturing management that appear in the literature as enabling elements of flexibility, their effectiveness as enabling elements may depend not only on their presence in a production unit, but also on the degree of their assimilation by the unit. Second, even tasks known to be transitory may need to be managed well, since successful response to a subsequent longer-lasting task may depend on mastery of skills required to carry out the transitory task.

The strong inter-subsystem effects observed in explaining line performance highlight the importance of analyzing manufacturing change at low level units of analysis. The literature on complexity (Simon 1960, 1979; Perrow 1967, 1984; Weick 1990) suggests that for complex systems, cause and effect relationships are unclear, problems are difficult to understand, and interactions and processes are poorly understood. The implication for the Operations Management literature comes from Simon's (1986) comment that no single principle exists for deductive prediction in a complex environment, and consequently, rational inquiry requires extensive empirical research at the 'micro-micro' level. This study comes closer to that level by using the production line rather than the factory as the unit of analysis. Given that more than 90% of empirical research in Operations Management uses the factory as the unit of analysis (Swink and Speier 1995), this research demonstrates the value of considering micro-level units for future research.

Several limits apply to the study. It would be useful to examine the temporal pattern in changed performance following changes in manufacturing requirements, to determine which types of changes lead to quick recovery and which lead to longer term reductions in performance. In addition, the study does not address several hierarchical levels and perspectives of focus within a manufacturing facility. Examination of advantages and disadvantages of focus at more hierarchical levels and from more perspectives is necessary for the development of an integrative theory of manufacturing focus. One major problem in such empirical examination is likely to be the measurement of focus. The list of determinants proposed in Table 4 is less than complete at the factory level, and only a beginning at the production line level. More serious problems, however, may lie in the measurement of the aspects of focus other than dimension, namely, manufacturing task, and tailoring of the system. Only recently have researchers begun to address the issue through measures based on perceptual information (Pesch and Schroeder 1996, Berry and Bozrath 1997). Nonetheless, we believe that the results contribute to our understanding of how changes in manufacturing requirements affect the performance of a focused factory.

In conclusion, our results contribute to the literature in several ways. First, this work connects research on manufacturing focus with that of organizational change. Specifically, we utilize the organizational nature of production units including their routines and absorptive capacity to analyze the limits and paths of changing the manufacturing requirements of production lines. Second, this work contributes to the research on manufacturing flexibility by rigorously examining the notion of volume heterogeneity as distinct from the concept of aggregate production volume flexibility.

Third, we provide evidence that the effectiveness of the enabling elements of manufacturing flexibility depend not only on their presence in a production unit, but also on the degree of their assimilation by the unit. Finally, the study contributes to the empirical literature in Operations Management by demonstrating the value of considering micro-level units of analysis along multiple dimensions of manufacturing requirements.

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[1] The International Assembly Plant Study was carried out under the auspices of the International Motor Vehicles Program (IMVP) at Massachusetts Institute of Technology. A consortium of automobile manufacturing companies, governments, and labor unions sponsored the five year research project.

[2] See for example, Tirole, Jean, 1989. "The Theory of Industrial Organization;" The MIT Press; Cambridge, MA, pp. 221-222.

Table 1. Literature Based Dimensions of Factory Focus

Focusing Dimensions	**Description**	**Examples**
Product	Products assigned to plants using product based criteria, including product life cycle	Appliances Consumer Electricals Canned Food Medical Instrument
Market/Customer	Plants dedicated to specific market(s) or customer(s)	Beverage Bottling Industrial Equipment Industrial Gas
Process	Segments of the production process assigned to different plants based on process based criteria	Automobiles Consumer Electronics Heavy Chemicals Rubber products Apparel
Volumes	High, low and medium volume products assigned to different plants	Industrial Equipment Consumer Durable
Geographic Region (Raw material based)	Each plant procures from a specified geographic region	Paper and pulp Lumber Meat Processing Agricultural products Mineral Processing
Geographic Region (Market area based)	Each plant produces for a specified geographic region	Energy Generation Printing Glass Asphalt/ Concrete

Table 2. Positioning Factories on the Focusing Dimensions

Dimension	Current Position, Factory F	Alternative Position, Factory F_1
Product	One product, an annealed component	Annealing an additional component
Process	Employs one technology, annealing	Begin tempering in addition
Customer	One assembly plant of its parent firm	Accepting orders from outside the firm
Geographic	Delivers to one location, the above assembly plant	Also sell to a distant downstream plant
Volume	Homogeneous volumes, large batches	Accepting additional small orders
Supplier	One machining plant of its parent firm	Accepting parts from outside the firm

Table 3. CR Proliferation 1986 vs. 1991 - By Customer Type

Customer Type	Quantity 1986	Quantity 1991	Models 1986	Models 1991
OEM	1,077,700	1,542,792	272	395
Export	22,745	226,003	83	320
Wholesaler	68,400	96,439	46	51
Subsidiary	6,459	16,449	40	65
Total Domestic	1,146,100	1,639,231	318	446
Total Export	29,204	242,452	123	385
Total	1,175,304	1,881,683	441	831

Table 4 Controlling Determinants and Hierarchical Linkage of Focus

Focusing Dimension	Controlling Determinant	Production Line Implication Along The Two Identified Dimensions
Product	Product-mix width (Kotler 1994, pp. 434-435)	# of parts on most lines
	Product line depth (Kotler 1994, pp. 434-435)	# of parts on most lines
	Product feature variety (McDuffie et al , 1996)	# of parts on some lines
	Product attribute variety (Anderson 1995)	# of parts on some lines
	Product customization	# of parts on some lines
	Packaging variety	# of parts on packaging lines
	Product-life cycle stages	# of parts on most lines
Volume	Range of order sizes	Heterogeneity of volume on most lines
	Delivery lot sizes for blanket orders	Heterogeneity of volume on some lines
	Allowable disruptions of production runs	Heterogeneity of volume on all lines
Customers	Number of customers	Likely volume heterogeneity
	Relative size of customers	Likely volume heterogeneity
	Product application	New part numbers
	Delivery requirements	Volume heterogeneity
	Inspection requirements	Part numbers with specific instructions[1]
	Conformance specifications	Part numbers with specific instructions[1]
	Market segments	New part numbers
Process	Process Life cycle stages	Part numbers, Volume heterogeneity
	Number of different technologies	New parts
	Nature of difference in technology	- -
	Materials processed	Parts on some lines
Geographic	Procurement area	Volume heterogeneity upstream
	Distribution area	Volume heterogeneity downstream
	Technological Standards	Additional parts/instructions[1] on some lines
	Government Regulations	Additional parts/instructions[1] on some lines
	Delivery requirements	Volume heterogeneity downstream
	Shipping requirements	Parts/instructions[1] on downstream lines
	Packaging requirements	Parts/instructions[1] on downstream lines
	Lead time	Volume heterogeneity downstream
Suppliers*	Number of suppliers	Volume heterogeneity upstream
	Supplier size range	Volume heterogeneity upstream
	Relationship mode (Shapiro 1985)	- -
	Incoming inspection requirements	- -

[1] Typically, a factory has its own system to *record* the instructions in the form of a traceable document (for example, a route sheet, or a standard operating procedure). This document, sometimes based on an alphanumeric extension of the relevant part number, can be counted as a separate part number for our purpose.

* Unlike the other dimensions, the supplier aspect of defocusing is not captured very well through line level measures. Often, complexities of supplier management are usually taken care of by the Materials function, and production lines are insulated from accompanying variations.

Table 5 Conceptual and Operational Variables for Hypothesis Testing

Hypothesis	Dependent variable		Independent variable		Expected Relationship
	Conceptual	Operational	Conceptual	Operational	
H1A	production line performance	machine line labor productivity	task change for which line lacks absorptive capacity	part mix breadth at the line	Negative
H1B	production line performance	machine line conformance quality	task change for which line lacks absorptive capacity	part mix breadth at the line	Negative
H1C	production line performance	machine line labor productivity	task change for which line lacks absorptive capacity	part volume heterogeneity at the line	Negative
H1D	production line performance	machine line conformance quality	task change for which line lacks absorptive capacity	part volume heterogeneity at the line	Negative
H2A	production line performance	assembly line labor productivity	task change for which line lacks absorptive capacity	part volume heterogeneity at the line	Negative
H2B	production line performance	assembly line conformance quality	task change for which line lacks absorptive capacity	part volume heterogeneity at the line	Negative
H2C	production line performance	assembly line labor productivity	task change for which line has absorptive capacity	part mix breadth at the line	No relationship expected
H2D	production line performance	assembly line conformance quality	task change for which line has absorptive capacity	part mix breadth at the line	No relationship expected
H3A	production line performance	machine line labor productivity	indirect task change for which line lacks absorptive capacity	part mix breadth at downstream line	Negative
H3B	production line performance	assembly line labor productivity	indirect task change for which line has absorptive capacity	part mix breadth at downstream line	No relationship expected

Table 6. Variables used in Testing Hypotheses Sets H1 and H2

Variable	Construct	Data Source
Focus Variables		
Part Mix	• Number of part-numbers	1986-1990: Actual production volumes by month for each of the 1,300 part numbers.
Part Volume Heterogeneity	• Hirschman-Herfindahl Index (HHI)* of part volumes	Same as above.
	• Variance of part volumes**	Same as above.
Performance Variables		
Labor Productivity	• Direct labor hours per unit • Indirect labor hours per unit	1986-1990: Actual direct and indirect labor hours by month by cost center.
	• Standardized direct and indirect labor hours per unit	Above actual hours, and work standards by year.
Conformance Quality (Internal Failure Cost)	• Scrap treatment hours per unit output	1986-1988: Actual labor hours by month.

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* For n variables $x_1, \ldots\ldots, x_n$, the index is defined as, $HHI = \Sigma x_i^2/(\Sigma x_i)^2$ for all $i = 1, \ldots, n$. See for example, Tirole, Jean, 1989. "The Theory of Industrial Organization;" The MIT Press; Cambridge, MA. pp. 221-222.

** For n variables $x_1, \ldots\ldots, x_n$, Variance $= (\Sigma(x_i - \Sigma x_i/n)^2)/n$ for all $i = 1, \ldots\ldots, n$.

Table 7: Results of Testing Hypotheses Sets H1, H2, and H3.

Hypothesis	Test Result	Description of Result
H1A	Rejected	Part mix breadth does not affect machining line labor productivity.
HIB	Partially supported	Part mix breadth detrimentally affects conformance quality at some machining lines.
H1C	Supported	Part volume heterogeneity detrimentally affects machining line labor productivity.
H1D	Supported	Part volume heterogeneity detrimentally affects machining line conformance quality.
H2A	Supported	Part volume heterogeneity detrimentally affects assembly line labor productivity.
H2B	Supported	Part volume heterogeneity detrimentally affects assembly line conformance quality.
H2C	Not rejected	Part mix breadth does not affect assembly line labor productivity.
H2D	Rejected	Part mix breadth detrimentally affects assembly line conformance quality.
H3A	Supported	Machining line labor productivity declines with downstream assembly line part mix breadth.
H3B	Not rejected	Assembly line labor productivity is not affected by downstream part mix breadth.

Table 8 Impact of Defocusing on Production Line Performance: Summary Results

	Defocusing Variable	Part Mix Breadth	Part Volume Heterogeneity	Downstream part mix breadth
Type of Production Line	**Performance Variable**			
Machining	Labor productivity	No impact	Detrimental impact	Detrimental impact
	Conformance quality	Partial detrimental impact	Detrimental impact	Not tested due to data limitations
Assembly	Labor productivity	No impact	Detrimental impact	No impact
	Conformance quality	Detrimental impact	Detrimental impact	Not tested due to data limitations

TABLE 9 Production Line[1] Labor Hours vs. Defocusing: Pearson Pairwise Correlation Coefficients

	Correlation Coefficients with Component Defocusing		
Labor Hours Per Unit[2, 3]	Number of Part Numbers	HHI of Volumes	Variance of Volumes
ML1 Direct Labor	.129, (.81)	.511, (3.94)****	.669, (5.97)****
ML1 Indirect Labor	.042, (.22)	.469, (3.52)****	.585, (4.79)****
ML1 Standardized Direct Labor	.226, (1.48)*	.431, (3.17)***	.499, (3.82)****
ML2 Direct Labor	.480, (3.37)****	.233, (1.6)*	.006, (.04)
ML2 Indirect Labor	.364, (2.38)**	.106, (.71)	.107, (.65)
ML2 Standardized Direct Labor	.464, (3.19)****	.217, (1.48)*	.015, (.09)
ML3 Direct Labor	.03, (.19)	.396, (2.9)***	.043, (.27)
ML3 Indirect Labor	.391, (2.59)***	.301, (2.08)**	.215, (1.34)*
ML3 Standardized Direct Labor	.096, (.59)	.298, (2.07)*	-.118, (.72)
ML5 Direct labor	.040, (.25)	-.144, (.97)	.370, (2.43)***
ML5 Indirect Labor	.157, (.96)	-.145, (.97)	.424, (2.85)****
ML5 Standardized Direct Labor	.056, (.31)	-.187, (1.26)	.416, (2.79)****
ML6 Direct labor	-.242, (1.54)*	-.007, (.04)	.029, (.16)
ML6 Indirect Labor	-.191, (1.19)	-.002, (.011)	-.1, (.54)
ML6 Standardized Direct Labor	-.3, (1.91)**	-.313, (2.16)**	-.199, (1.09)
ML7 Direct Labor	-.049, (.3)	.010, (.07)	.116, (.711)
ML7 Indirect Labor	.285, (1.79)**	.049, (.32)	.080, (.49)
AL1 Direct Labor	-.433, (2.91)***	-.006, (.04)	.302(2.07)**
AL2 Direct Labor	-.142, (.87)	-.153, (1.02)	.466, (3.21)***
AL3 Direct Labor	-.035, (.21)	.427, (3.13)****	.016, (.099)
AL4 Direct Labor	.292, (2.01)**	.189, (1.28)	.234, (1.47)*
AL4 Indirect Labor	.13, (.79)	.395, (2.84)****	.247, (1.55)*
AL5 Direct Labor	-.08, (.52)	.347, (2.45)***	.266, (1.83)*
AL5 Indirect Labor	.194, (1.31)*	.021, (.14)	-.208, (1.41)*
AL6 Direct Labor	.291, (1.97)**	-.303, (2.11)**	-.217, (1.47)*
AL7 Direct Labor	-.121, (.81)	.079, (.52)	-.142, (.94)
AL8 Direct Labour[4]	.297, (1.97)**	.078, (.52)	-.179, (1.2)

**** indicates statistical significance at 99.9% confidence level.
*** indicates statistical significance at 99% confidence level.
** indicates statistical significance at 95% confidence level.
* indicates statistical significance at 90% confidence level.

1: One line, ML4, is not amenable to statistical analysis, due to data limitations.
2: Standard hours have not changed on all lines.
3: Indirect labor is negligible at most assembly lines.
4: Accuracy of data at AL8 is suspect due to the relative lack of managerial attention to this line, which does packaging. Results at AL8 are presented here for completeness, but not included in the discussion.

Table 9A. Signs and Significance of the Coefficients of Table 9

		Number of Coefficients		
		Positive (significant at 90%, significant at 95%, significant at 99%)	Negative (significant at 90%, significant at 95%, significant at 99%)	Total
1	Machining Lines			
1a	Number of Part Numbers	13 (6, 5, 3)	4 (2, 1, 0)	17
1b	HHI of Part volumes	11 (8, 6, 4)	6 (1, 0, 0)	17
1c	Variance of Part volumes	14 (7, 6, 6)	3 (0, 0, 0)	17
2	Assembly Lines			
2a	Number of Part Numbers	4 (3, 2, 0)	5 (1, 1, 1)	9
2b	HHI of Part volumes	6 (3, 3, 3)	3 (1, 1, 0)	9
2c	Variance of Part volumes	6 (5, 2, 1)	3 (2, 0, 0)	9

Table 9B Deterioration in Performance at the Production Lines

		Observed	Not Observed
Deterioration of Labor Productivity with Increasing Heterogeneity of Volumes	*Not Observed*	ML2 Indirect Labor ML7 Indirect Labor AL6 Direct Labor AL5 Indirect Labor	ML6 Direct Labor ML6 Indirect Labor ML7 Direct Labor AL7 Direct Labor
	Observed	ML1 Standardized Direct Labor ML2 Direct Labor ML2 Standardized Direct Labor ML3 Indirect Labor AL4 Direct Labor AL4 Indirect Labor	ML1 Direct Labor ML1 Indirect Labor ML3 Direct Labor ML3 Standardized Direct Labor ML5 Direct Labor ML5 Indirect Labor ML5 Standardized Direct Labor ML6 Standardized Direct Labor AL1 Direct Labor AL2 Direct Labor AL3 Direct Labor AL5 Direct Labor

Deterioration in Labor Productivity with Increasing Number of Parts

TABLE 10 Scrap Treatment Labor Hours vs. Component Defocusing: Pearson Pairwise Correlation Coefficients

	Correlation Coefficients with Component Defocusing		
	Number of Part- Numbers	HHI of Volumes	Variance of Volumes
Machining Line 1	.216 (.82)	.375 (1.56)*	.252 (1.01)
Machining Line 2	.646 (2.93)***	.291 (1.18)	.316 (1.16)
Machining Line 3	.416 (1.58)*	.300 (1.22)	.390 (1.46)*
Machining Line 5	-0.253 (.9)	.034 (.132)	.406 (1.54)*
Machining Line 6	.597 (2.57)***	.088 (.34)	-0.361 (1.33)*
Machining Line 7	.292 (1.06)	.561 (2.63)***	.682 (3.09)***
Assembly Line 1	.429 (1.64)*	.334 (1.38)*	.087 (.304)
Assembly Line 2	.197 (.69)	-0.045 (.17)	.358 (1.32)*
Assembly Line 3	.376 (1.40)*	.018 (.069)	.530 (2.16)**
Assembly Line 4	.527 (2.15)**	.244 (0.96)	.648 (2.94)***

*** indicates statistical significance at 99% confidence level.

** indicates statistical significance at 95% confidence level.

* indicates statistical significance at 90% confidence level.

Note 1: ML4 is not amenable to statistical analysis, due to data limitations.

Note 2: Focusing variables at four assembly lines, AL1, AL2, AL3, and AL4, can be used as independent variables for these tests. At the other assembly lines, the 'parts' have the same mix as the final product, and therefore become factory-level rather than line level variables. This difficulty did not arise with productivity data, since the labor hours are collected at each line, unlike the dependent variable here, which is measured only at the factory level.

Table 10A Signs and significance of the coefficients of Table 10

		Number of Coefficients		
		Positive (significant at 90%, significant at 95%, significant at 99%)	Negative (significant at 90%, significant at 95%, significant at 99%)	Total
1	Machining Lines			
1a	Number of Part Numbers	5 (3, 2, 2)	1 (0, 0, 0)	6
1b	HHI of Part volumes	6 (2, 1, 1)	0 (0, 0, 0)	6
1c	Variance of Part volumes	5 (3, 1, 1)	1 (1, 0, 0)	6
2	Assembly Lines			
2a	Number of Part Numbers	4 (3, 1, 0)	0 (0, 0, 0)	4
2b	HHI of Part volumes	3 (1, 0, 0)	1 (0, 0, 0)	4
2c	Variance of Part volumes	4 (3, 2, 1)	0 (0, 0, 0)	4

Table 11 Downstream[1] Proliferation vs. Upstream Line Labor Hours

	Direct Labor	Indirect labor	Standardized Direct Labor
Machining Line 1	.654, (5.72)***	.475, (3.57)***	.457, (3.4)***
Machining Line 2	.564, (4.56)***	.286, (1.97)	.559, (4.47)***
Machining Line 3	.101, (.67)	.508, (3.91)***	.207, (1.4)
Machining Line 4	.328, (2.33)*	.01, (.07)	.175, (1.18)
Machining Line 5	.639, (5.51)***	.412, (2.99)**	.653, (5.71)***
Machining Line 6	.284, (1.96)*	.151, (1.01)	.504, (3.82)***
Machining Line 7	-.107, (.71)	.368, (2.62)**	N/A
Assembly Line 1	-.047, (.31)	N/A	N/A
Assembly Line 2	.197, (1.33)	N/A	.145, (.99)
Assembly Line 3	-.004, (.02)	N/A	N/A
Assembly Line 4	-.042, (.27)	.661, (5.84)***	N/A
Assembly Line 5	-..08, (.52)	.194, (1.3)	N/A
Assembly Line 6	.297, (2.06)*	N/A	-.2, (1.38)
Assembly Line 7	-.121, (.59)	N/A	N/A

*** indicates statistical significance at 99.9% level of confidence.

** indicates statistical significance at 99% level of confidence.

* indicates statistical significance at 95% level of confidence.

N/A: Not applicable, due to, i) absence of indirect labor, or, ii) no change in standards, as appropriate.

[1]: The downstream product for machining lines (ML1 through ML7,) and subassembly lines AL1 through AL3 is the compressor without peripherals, while that for assembly lines AL4 through AL7 is the compressor with peripherals, as explained in Section 3.

Table 11A Signs and significance of the coefficients of Table 11

		Number of Coefficients		
		Positive (significant at 90%, significant at 95%, significant at 99%)	Negative (significant at 90%, significant at 95%, significant at 99%)	Total
1	Machining Lines			
1a	Direct Labor Hours	6 (5, 3, 3)	1 (0, 0, 0)	7
1b	Indirect Labor Hours	7 (4, 4, 2)	0 (0, 0, 0)	7
1c	Standardized Direct Labor Hours	6 (4, 4, 4)	0 (0, 0, 0)	6
2	Assembly Lines			
2a	Direct Labor Hours	2 (1, 0, 0)	5 (0, 0, 0)	7
2b	Indirect Labor Hours	2 (1, 1, 1)	0 (0, 0, 0)	2
2c	Standardized Direct Labor Hours	1 (0, 0, 0)	1 (0, 0, 0)	2

Figure 1. Focus Map

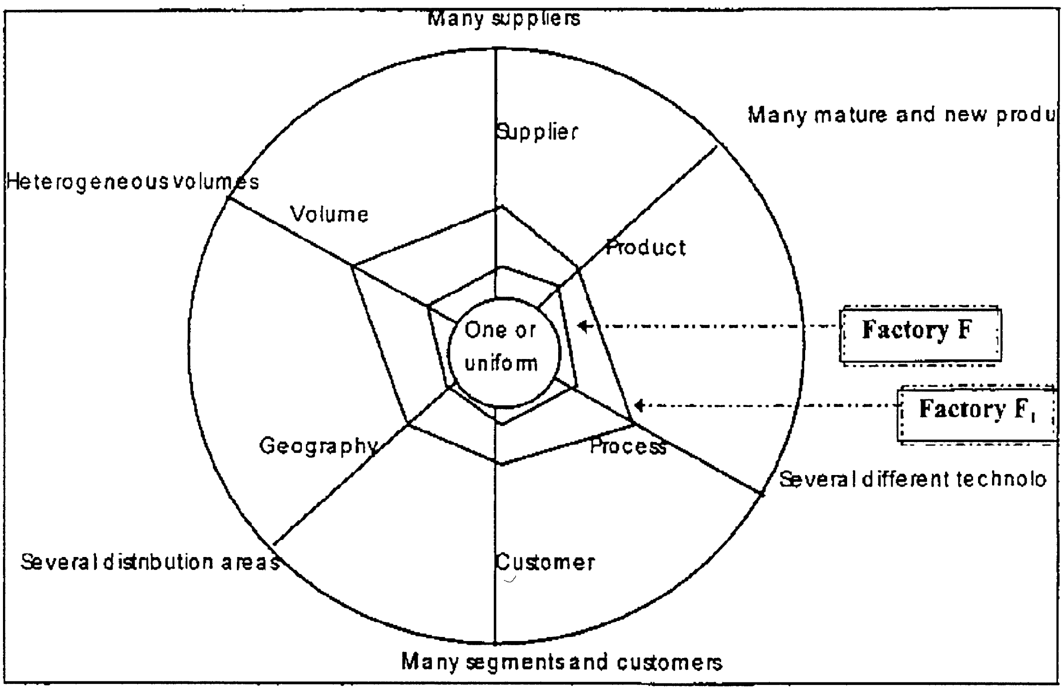
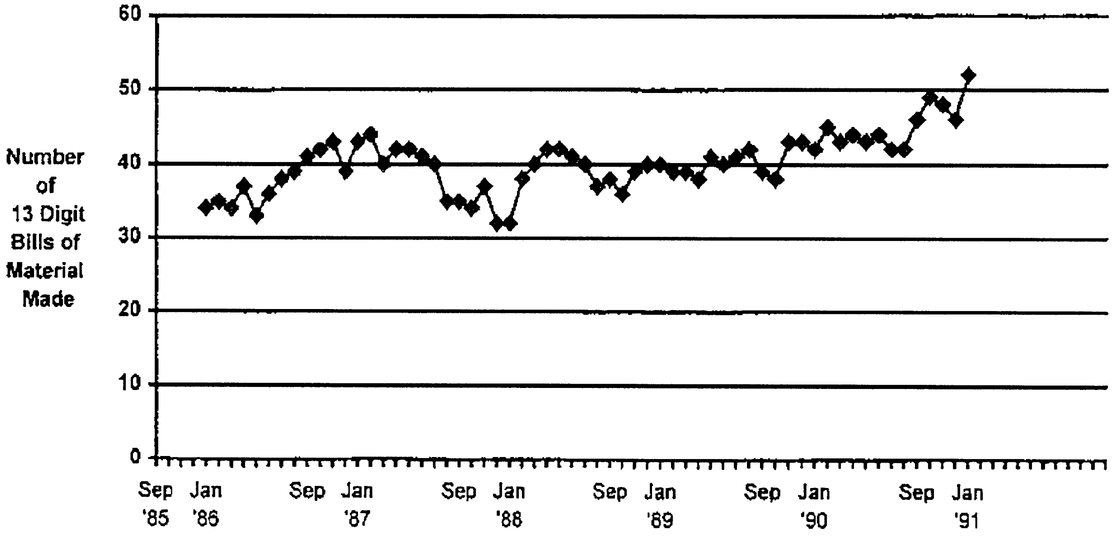


Figure 2.1 **13-Digit Product Proliferation of Basic Compressors: 1985 - 1991**



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