1. Introduction

The machine tool industry is very small in relationship to the whole of industry. According to Jones [1], it accounts for between one and three percent of those employed in manufacturing industry in the developed countries. However, the machine tool industry has a proportionally greater impact on industrial development because it is an important mechanism for the transmission and diffusion of the latest machining technology throughout industry [2]. As the MTTA [3, p. 2] puts it: "No modern product exists without machine tools, if not directly involved then certainly only one remove away." It is this centrality of the machine tool in modern industry, as well as its role as a generator and transmitter of new technology, which is the core of its strategic function in industrialized countries and the main reason why many governments intervene in the market and foster the local machine tool industry. This paper deals with the relationship between radical (or major) technical change and economic performance in this strategic industry.

The machine tool industry experienced large structural changes in the second half of the 1970s and in the early 1980s. In this period, some Japanese machine tool firms perceived the opportunities opened up by microelectronics technology and set in motion a process whereby numerically controlled machine tools came to substitute for conventional machine tools on a large scale. In the process, Japanese firms gained very large market shares in the machine tool industry at the expense of the U.S. industry, which was nearly annihilated and the European industry, which was given a severe blow.

However, a new substitute, flexible manufacturing systems (FMSs), is now gaining importance in the machine tool industry. In particular, in the segment of machining
centers (a combined milling, drilling, and boring machine), this new substitute has gained significant market shares and it is European (especially German and Italian) machine tool firms that dominate the FMS market. These firms have, indeed, gained a substantial lead in the growing FMS market.

The main purpose of this paper is to discuss whether the European machine tool industry will be able to use flexible manufacturing systems as a basis for a sustainable revival. We believe the answer to be no. The intriguing question which then arises is; why should this new substitute fail to restructure the industry when the substitution of numerically controlled machine tools (NCMTs) for conventional machine tools was associated with very large structural changes? This, of course, raises the general question of under what conditions a large technical change will have a disruptive effect on an industry. While our main objective is answering the empirical question as to the possible revival of the European machine tool industry, we will also touch upon this broader analytical issue.1

The paper is set out in the following way. In section 2, we give a few analytical points of departure. We list a set of factors which influence the evolution of industries. These factors, we argue, are very closely linked to those which have a major influence on the diffusion of a new substitute. Thus, the process of substitution is seen as driven by much the same factors as those that shape the structure of the supplying industry. In section 3, we use this framework to describe how the Japanese firms gained market shares in NCMTs in the period 1975–1985. In section 4, we describe the technology of the new substitute, flexible manufacturing systems, and how it has been diffused. The present structure of the industry is analyzed in section 5 where we indicate the competitive position of the leading European firms. In section 6, we use our framework to discuss how a set of technical and economic trends may influence the structural elements of the machine tool industry of the 1990s and, on this basis, judge whether or not FMS can provide the foundation of a revival of the European machine tool industry.

2. Analytical Points of Departure

Within a given industrial structure, technical change normally takes place in small increments where the prevailing and dominant design provides the framework and the limits to development [6]. This evolutionary process is from time to time punctuated by a discontinuous change in which a new product with substantially better (actual or potential) price/performance ratio, caused by a substantially changed technology base,2 is put on the market. Such technological discontinuities are commonly found to be the starting points for major change in industrial structure [6–11]. The electronic watch, for instance, replaced mechanical watches and at the same time altered the structure of the watch industry to one relying a great deal more on scale economies and on a totally different set of technological capabilities, i.e., the firms had to build up a competence in some new technical fields, while other technologies were made obsolete. With such a discontinuity, the entry barriers to the various strategic groups (see [12]) in an industry may alter greatly, leading to the entry of an entirely new set of actors. Indeed, some of the more disruptive technological discontinuities have been initiated by firms outside an industry which were in a position to draw on a different technology base [6, 7].

Even with a very large change in the product’s technology base, the technical and

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1For a tentative discussion of this issue, see Granstrand and Jacobsson [4] and Ehmberg and Sjöberg [5].
2By a product’s technology base is meant all the technologies—specific areas of technical competence—which are needed to design and produce the product.
economic elements of the industry’s structure would not be expected to be altered in any significant way unless the new substitute becomes widely diffused among buyers. Technological discontinuities, diffusion of a new substitute, and structural changes in the supplying industry are thus to be expected to be closely linked.

A list of commonly identified factors influencing the evolution, or revolution of industry structure is provided by Porter [12, p. 164]. We label these factors *driving forces* of structural change in industries. These include product and process innovations, but also a whole set of other factors:

1. Buyers’ knowledge about new products
2. Reduction of uncertainty among suppliers and buyers
3. Changes in buyers’ segments served
4. Diffusion of proprietary knowledge
5. Increases in scale
6. Accumulation of experience
7. Product, process, and marketing innovations
8. Entries and exits from the industry by companies
9. Changes in adjacent industries

Of course, these factors interact. For instance, reduction in uncertainty among buyers may lead to an increase in demand and a subsequent increase in scale and accumulation of experience in the supplier industry. Moreover, changes which these factors induce in one element of industrial structure tend to lead to changes in other elements [12, p. 184].

![Image](https://via.placeholder.com/150)

Given that the initial structure varies greatly between industries and that there can be many combinations of changes in the underlying elements of structure, one cannot expect there to be a “typical” pattern for an industry’s evolution.

Although a great number of factors have been identified as having a bearing on the rate and level of diffusion of a new substitute [e.g., 13–17], three can probably be said to be the most fundamental for buyer diffusion.

First, the single most important factor appears to be the *price/performance ratio* of the new substitute as compared to the product it is intended to substitute for. Initially, the price of the new product is normally higher than that which it may eventually replace. At the same time, the new product is often very crude and surpasses the old product in perhaps only one or a few of its performance dimensions. This, or these, dimensions, though, can be of critical importance for a particular segment of the market. The first transistor, for instance, although technically very basic, quickly replaced vacuum tubes in hearing aids [11, p. 29].

Over time, the new product improves both its performance and price competitiveness vis-à-vis the old product. How this relationship develops is in part a function of numbers 5, 6, and 7 of the *driving forces* of structural change; namely, expansion of scale (affecting costs), the accumulation of experience (affecting costs and product performance), and innovative behavior (affecting costs and product performance) of the supplying industry. All these factors can be affected by the individual supplier’s investment decisions. A powerful investment by a single firm or by a group of firms in the supplying industry can therefore speed up the diffusion by improving the price/performance ratio of the new substitute.

Second, the optimal price/performance ratio usually varies between buyer segments as does the *type* of performance required (e.g., the ability to machine complex shapes versus user friendliness of a machine tool). The speed of diffusion therefore depends on
the supplying industry’s ability to differentiate their products so that they match the
demand from a whole range of heterogeneous buyer segments (i.e., driving force number
3). Consequently, the skill with which the supplying industry identifies these varying
demands and the emphasis that it places on developing the appropriate performance
dimensions and achieving the right price levels affect diffusion.

Third, the potential customer needs information and knowledge about the new sub-
stitute in order to become aware of its existence, assess it, take the risk of investing in
and operating it. Buyer learning and reduction in uncertainty (i.e., force numbers 1 and
2) are critical factors here. These can be influenced, for example, by demonstration effects
of the new product but the supplying industry can greatly influence these factors also.
First, through its marketing and distribution function, it can increase buyers’ learning.
Second, by making the new substitute more reliable (e.g., by systematizing experience)
and providing a service function of high standard, it can reduce technological uncertainties
perceived by the buyers.

Hence, the main factors determining the diffusion of a new product and how it
comes to substitute for existing products are much determined by the same factors which
shape industrial evolution. These factors are, furthermore, affected directly by individual
firms in the supplying industry when they make their investment decisions.


In the early 1950s, the first numerically controlled machine tool (NCMT) was de-
developed; instead of having a worker controlling the movements of the tools and setting
the operation speed and other production parameters, the information needed was put on
a medium, e.g., a tape, and fed into a numerical control unit. By simply changing tapes,
the NCMT could quickly be switched from the production of one part to another. Flex-
ibility and automation had started to combine.

Because of the high costs and the unreliability of these early NCMTs, the new
substitute was not diffused to any significant extent until the early 1970s when the
numerical control unit was based on a minicomputer. A still more significant change was
the introduction of microcomputer based control units in 1975 which set in motion a
process whereby the price/performance ratio of NCMTs greatly improved.

The use of microelectronics resulted in lower costs, increased flexibility, greater
reliability, simpler programming, and the automation of tasks other than those mentioned
above. Automatic tool changing is normal today, automatic material handling equipment
is often attached to the machine tool and the task of supervising the whole production
process is beginning to be automated with the help of, for example, sensors.

These technical and economic developments have much contributed to the fast
diffusion of NCMTs since the mid-1970s, as is clearly visible in Figure 1, and to a
substitution for manual machine tools. In 1976, machining centers accounted for only
36 percent of the production of machines performing milling; the share rose to 68 percent
in 1988. For lathes, the figure is even higher—80 percent [19].

The substitution process briefly outlined above has been associated with a very
marked shift in the geographical location of production to the benefit of Japan. In Figure
2, market share data is plotted for the three regions; Japan, Europe, and the U.S. with
respect to CNC (Computer Numerically Control) lathes and machining centers.

1Diffusion of proprietary knowledge (driving force No. 4), entry of new firms (No. 8) and government
intervention (No. 10), also affect diffusion but mainly indirectly via one or several of these factors.
Growth in the stock of NCMTs in the USA for periods of five years (number of NCMTs)

![Graph showing the growth in the stock of NCMTs in the USA for periods of five years.]

**Fig. 1.** The diffusion pattern of numerically controlled machine tools in the U.S. *Source: American Machinist* (July 22, 1963; November 18 (part 2) 1968; October 29, 1973; December 1978; November 1983; November 1989) [18].

CNC Lathes

![Graph showing the production of CNC lathes in Japan, Europe, and the U.S. 1975-1988 (units).]

TABLE 1

<table>
<thead>
<tr>
<th>Production of Machining Centers by Leading Firms in Japan, 1975 to 1988 (in Units)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top firm</td>
</tr>
<tr>
<td>Average of the following four firms</td>
</tr>
</tbody>
</table>


The dominance of Japan—which produces nearly three-quarters of these machines—is very evident and painful for other countries, especially for the U.S. industry which has almost been annihilated.4

How then was the Japanese industry able to alter the balance so totally in this industry? A short5 answer is: they identified the key driving forces of structural change referred to above and implemented new company strategies based upon these forces.

In the early 1970s, the machine tool industry had, as a rule, not yet identified numerically controlled machine tools as the key product(s) around which they should define their strategies. Although there was some trade in NCMTs, the business relations were mainly of a local or regional character. Small volumes only were produced and the main customers were large firms. These companies often demand high performance machines, frequently with custom designed features.

In the mid-1970s, some Japanese companies (especially Okuma, Mori Seiki, and Yamazaki) started to apply a business strategy which sought to penetrate very large parts of the engineering industry, i.e., to diffuse NCMTs widely at the expense of conventional machine tools. The NCMTs were primarily, but not exclusively, aimed at the smaller and medium sized firms which were catered for by indirect sales (i.e., through independent machine tool distributors rather than subsidiaries of the machine tool companies).

The key factor involved the design of lower performance, smaller, and lower cost CNC lathes and machining centers than those that hitherto had been available to customers. Access to microcomputer based CNC units was a critical factor. The development of microcomputer CNC units was pioneered by the Japanese firm Fujitsu Fanuc which gave Japanese machine tool firms a temporary advantage6 over their European and U.S. competitors. So the Japanese firms deliberately tried to, and succeeded in, opening up a new market for this new variant of NCMTs. Their success enabled them to grow in size and to gain what were hitherto only potential economies of scale and experience.

As a consequence, the size of the leading firms grew phenomenally. Available data on the yearly production volumes of Japanese companies producing machining centers7 are summarized in Table 1. It is apparent that the Japanese firms have become very large in this industry, with volumes of up to 1700 machining centers per year. By way of comparison, the largest non-Japanese firm produces less than 500, and many firms produce only about 100 units per year.

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4The U.S. share of the production of CNC lathes fell from 36 percent in 1975 to 6 percent in 1988! In machining centers, the U.S. share fell even more, from 42 percent in 1978 to 8 percent in 1988 [19].

5The following paragraphs are based on Jacobsson [20] which contains a longer discussion.

6It was not until 1980 that the first U.S. CNC-unit producer introduced a microcomputer based CNC unit [21].

7For data on the case of CNC-lathes, see Ehrnberg and Jacobsson [19].
In conclusion, the rapid diffusion of NCMTs after the mid-1970s was intimately connected to the behavior of the supplying industry, in particular a handful of firms in Japan. In S-curve terminology, these firms created the point of maximum curvature and induced the industry to move upwards on the S-curve. In doing so, they were greatly aided by product innovation in an adjacent industry (driving force 9), i.e., the one supplying the control unit. A series of product and marketing innovations (force 7) were aimed at changing the buyer segments served (force 3). A process of increasing returns began to take place whereby scale and experience economies (forces 5 and 6) could be reaped. Price/performance ratio improved further and the rate of diffusion increased with a consequent increase in buyers learning and a reduction in their uncertainty (forces 1 and 2) about the new substitute.

The process described here came to an end in the mid-1980s. We can now discern the beginning of a new technological discontinuity which involves the diffusion of FMSs. In the remaining part of the paper, we will discuss whether this new discontinuity will be associated with the revival of the European machine tool industry. We will begin by describing this new substitute and briefly discuss the extent to which it has been diffused.

4. FMS—The Product and Its Diffusion

A flexible manufacturing systems (FMS) is defined here as a fully, or nearly fully, automated system which consists of at least two NCMTs, interconnected by means of an automated system for the handling and storage of material and sometimes tools, and controlled by an integrated computer system or a programmable logical circuit (PLC). The number of NCMTs in FMSs can be well over 20 machines, but is usually much less.

For large FMSs, a computer of the VAX-type (a minicomputer) controls the system. These systems can be called intelligent systems and include functions like order management, workpiece management, tool management, CNC-program management, and diagnostic functions. For less sophisticated, and normally smaller systems, a PLC is sufficient to control the system. We call these systems unintelligent systems.

The main advantage of an FMS is that it provides flexible automation. Compared to stand alone machines, which are flexible but require direct labor, an FMS has a higher level of automation. When compared to a transfer line (fixed automation) an FMS is more flexible in terms of the number of different parts that can be produced and in terms of ease of changes in design (and type) of products produced. On the whole it is true that small FMSs substitute for stand alone machines, and larger ones substitute for transfer lines or large systems of stand alone machines.

The first FMS was installed in 1965 in the U.S. [27]. By 1970, all in all, eight systems had been installed, a figure which grew to about 1000 in 1988 (see Table 2). These systems are based chiefly on machining centers—in 1985 two-thirds of the stock of FMSs incorporated only machining centers. Since making a system flexible is a much.

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8Often an FMS is defined from the point of view of the users, i.e., how flexible it is to be run, etc. In this paper the definition is based on the type and composition of the equipment, since the study mainly concerns the equipment suppliers.

9In a sample of 655 FMS installations (with a minimum of two machine tools), 46% of them included 2 to 4 NCMTs [25].

10Flexible manufacturing systems are introduced to meet four general objectives [26, p. 69]: improved machine utilization, reduced costs for work in progress, increased labor productivity, and greater flexibility of the equipment as compared to fixed automation machinery.
TABLE 2
Stock of Multi-Machine FMSs (Number of Installations) in Western Europe, the U.S., Japan and World-Wide (1970 to 1989); the Average Annual Growth Rate in the Stock of FMSs and the Distribution between Systems of Different Types

<table>
<thead>
<tr>
<th>Year</th>
<th>Western Europe (units)</th>
<th>U.S. (units)</th>
<th>Japan (units)</th>
<th>World Wide (units)</th>
<th>Growth Rate (%)</th>
<th>MCs (%)</th>
<th>CNC- Lathes (%)</th>
<th>Both MCs and CNC-Lathes (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1970</td>
<td>0</td>
<td>5</td>
<td>3</td>
<td>8</td>
<td></td>
<td>80</td>
<td>20</td>
<td>0</td>
</tr>
<tr>
<td>1975</td>
<td>2</td>
<td>8</td>
<td>25</td>
<td>48</td>
<td></td>
<td>68</td>
<td>30</td>
<td>2</td>
</tr>
<tr>
<td>1980</td>
<td>27</td>
<td>28</td>
<td>71</td>
<td>163</td>
<td></td>
<td>69</td>
<td>25</td>
<td>6</td>
</tr>
<tr>
<td>1985</td>
<td>208</td>
<td>90</td>
<td>166</td>
<td>553</td>
<td></td>
<td>69</td>
<td>22</td>
<td>9</td>
</tr>
<tr>
<td>1988</td>
<td>410</td>
<td>170</td>
<td>190</td>
<td>1000</td>
<td></td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
</tr>
<tr>
<td>1989</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>1200*</td>
<td></td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
</tr>
</tbody>
</table>

*aIn the source [IIASA, 1989] [28] the types of systems are called systems for prismatic, rotational, and both types of parts.
*bIncludes Belgium, Finland, France, FRG, Italy, the Netherlands, Norway, Sweden, U.K. (1975 to 1985) and FRG, U.K. France, Italy, Sweden, the Netherlands, Finland (1988).
*cAverage annual growth rate for the period of five years.
*dMCs = machining centers.
*eEstimate for the spring of 1989, not the end of the year.


more complicated task for CNC lathes than for machining centers, relatively few multi-machine systems based on CNC lathes are in operation.\footnote{See [19] for a further discussion on the reasons for this. More details on the diffusion of CNC-lathe systems are also given in that paper.}

In spite of its long history, FMSs have not greatly substituted for stand alone NCMTs. With an average number of 7.4 NCMTs in a system [25], an estimated total number of 7400 NCMTs had been incorporated in FMSs by 1988. This figure could be compared to a total stock of about 200,000 NCMTs in the U.S. alone in 1989 [18] and 80,000 in the Federal Republic of Germany in 1988 [31]. Thus, only a fraction of the global stock of NCMTs is incorporated in FMSs.

As far as the flow of FMSs is concerned, Table 3 shows an estimate of the market share of FMSs in 1988. Only approximately 4 to 5 percent of the machining centers sold in 1988, and as little as about 1 percent of the CNC lathes, were made part of a system with two or more NCMTs.\footnote{The diffusion is much faster in Sweden. Already in the mid-1980s, 16 to 20 percent of the sales of NCMTs were incorporated in a system [26, p. 75].}

However, when the value of the total systems (including machines, information system, material flow system, software, planning, training, etc.) is considered, FMSs constitute a significant share of the machining centers market, 21 to 29%, and 7 to 10%
TABLE 3
An Estimate of the Share of Multi-Machine FMSs in the Total Production of Machining Centers and CNC Lathes (1988)

<table>
<thead>
<tr>
<th></th>
<th>1) Machining Centers</th>
<th>2) CNC Lathes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production in 1988</td>
<td>(units and value)</td>
<td>(No. of machines and total value of the system)</td>
</tr>
<tr>
<td>Units</td>
<td>19,300</td>
<td>709–1,025 MCs</td>
</tr>
<tr>
<td></td>
<td>3,332 M$</td>
<td>780–1,128 M$</td>
</tr>
<tr>
<td>Units</td>
<td>31,400</td>
<td>255–373 CNC Lathes</td>
</tr>
<tr>
<td>Value</td>
<td>3,217 M$</td>
<td>230–336 M$</td>
</tr>
</tbody>
</table>

1The production in 1988 in France, FRG, U.K., Italy, India, Japan, Korea, Spain, Taiwan, and the U.S. (Elaboration on data supplied by CECIMO (1988) [32].)
2Ranta and Tchijov (1989) estimate the growth of FMSs to be 15% annually. Ranta (n.d.) estimates the accumulated number of FMSs to be 1000 in 1989, and with a 15% growth rate this implies that 130 FMSs were installed in 1988. Elaboration on data supplied by Boston Consulting Group [33] gives that 190 FMSs were installed in 1988. Thus 130 to 190 FMSs were installed in 1988. According to Table 2 69% of the systems only contain MCs, which gives 90 to 130 FMSs with only MCs. In a sample of 758 cases the mean value of no. of NCMTs in an FMS installation was 7.4 (Tchijov, 1989, p. 13). This gives 666 to 962 MCs. In Table 2 9% of all FMSs include both CNC lathes and MCs. Assuming that 50% of these machines are MCs, we have to add 43 to 63 (130*0.09*7.4*0.5–190*0.09*7.4*0.5) MCs, which gives the total number of 709 to 1025 MCs.
3In a sample of 44 FMS installations (for prismatic parts) made in 1985 to 1988 in the FMS World Data Bank the mean investment in FMSs was 1.1 M$ per machining center. For CNC lathes the mean investment value was 0.9 M$ per CNC lathe in a sample of 17 installations for rotational parts (1985 to 1988) in the same data base as above. (709*1.1 = 780; 1025*1.1 = 1128; 250*0.9 = 230; 373*0.9 = 336).
4 Using the same method as for MCs (see note b above), gives (0.22 + 0.045)*7.4*130 = 255 and 0.22 + (0.045)*7.4*190 = 373.
5The total size of the market (defined as NCMTs and FMSs) is for MCs 3761 to 3952 M$ and for CNC lathes 3343 to 3402 M$ (assuming that 45% of the FMS value is NCMTs—see Table 4).

of the CNC lathe market (see Table 3).13 Not surprisingly, FMSs have had a discernable impact on the firms in the machine tool industry, especially those supplying machining centers, a topic which will be discussed in the next section.

5. Industry Structure and Firms Strategy: FMS

The FMS industry overlaps with large sections of the machine tool industry. With the exception of some software firms which are active in the system integration function14 and specialized material handling firms, the FMS industry consists of a quite limited number of firms, many of which are large machine tool firms. These firms do not normally specialize in supplying FMSs but have a broader product portfolio, including both stand

13The reasons for this substantial discrepancy is that the NCMTs used only amount to 35 to 55 percent of the total investment in FMSs (see Table 4) and are often relatively advanced and of high cost.
14System integration is the function of integrating the information flow, the machine tools, and the material flow into one functioning unit. It is closely connected to the supply of the information system, since it includes a large amount of software engineering. The larger the number of different pieces of production equipment (NCMTs, robots, etc.) and the greater the demand for flexibility, the more complex the flows of material and information will be, as well as the system integration. Furthermore, installing and implementing an FMS requires a great deal of planning and training. The project management can either be performed by the supplier or by the customer, depending on which has the system responsibility.
The core of the FMS industry supply FMSs based on machining centers and in Figure 3 we attempt to capture some essential characteristics of that part of the machine tool industry. On the axes, we have placed two critical factors defining the nature of competition in the industry. On the vertical axis are the two basic ways for a firm to compete—cost leadership or differentiation. Either the firm competes with price or by providing a product/service for the customer which is unique. Examples could be a superior cutting speed of a machine or the ability to supply very large systems. The annual production volume of NCMTs is used as an indicator of cost leadership versus differentiation since significant scale and scope economies exist in the industry.

On the horizontal axis we have chosen to distinguish between machine oriented and systems oriented firms. The accumulated number of FMS installations made by a firm is

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For an analysis of the present CNC lathe industry see Ehrnberg and Jacobsson [19].
here used to indicate whether or not it is system oriented\(^\text{16}\) (see Appendix Table 1). Combining these two dimensions leads to four different broad strategies for competition in this industry. A firm can supply machines with price as the prime basis for competing or it can focus on supplying machines which are differentiated in some way. A firm can also compete with relatively cheap systems or with systems which are unique in some way.

In the southeast square, we find those firms pursuing a strategy of differentiation based primarily on intelligent systems—\textit{systems oriented differentiators}. Comau (Italy) and Werner und Kolb (Germany) as well as Scharmann (Germany) and Mandelli (Italy) follow this strategy. It could also be argued that the German transfer line and machining center supplier Huller Hille follows a system oriented differentiation strategy with respect to its machining centers. Huller Hille is fundamentally a system oriented firm on account of its strong position in transfer lines. In addition, it has a significant activity in smaller, PLC controlled systems and is now developing the market for intelligent systems. In these efforts it draws systematically on its wider scope advantages from its transfer line business, especially that dealing with flexible transfer lines.

Taken jointly, the competitive strength of these European firms in the FMS field is very significant. Up to 1988, these firms (excluding Huller Hille) jointly accounted for 42 percent of the accumulated sales of intelligent FMSs in Europe and the U.S. \cite{33} with Werner und Kolb as the leader.\(^\text{17}\)

In the northwest square, with \textit{machine oriented cost leaders}, we find the Japanese firms which were instrumental in restructuring the entire machining center (and CNC lathe) industry in the second half of the 1970s and the early 1980s, as described in section 3. The main firms involved here are Yamazaki, Okuma, and Mori Seiki. They are active in machining centers, CNC lathes, and to a varying extent, in FMSs built around these machines. These firms produced annually around 4000 machining centers and CNC lathes (units) by the end of the 1980s and jointly accounted for more than a third of the production of such machine tools in the OECD \cite{39}.\(^\text{18}\)

Two German firms, Deckel and Heller, also follow the same strategy, at least partly. Deckel is a global market leader in CNC milling and boring machines and is also active in machining centers. Heller, with one leg in the transfer line industry, has a second and powerful leg in the volume production of very price competitive machine centers (even by Japanese standards). Heller is the largest non-Japanese firm of machining centers and seems to be the only European machining center firm which directly competes with the Japanese.

Some of the firms which today pursue a machine oriented cost leadership strategy are also quite large in FMSs (see Appendix Table 1 and Figure 3). In particular, this applies to one Japanese company, Hitachi Seiki, which had by 1988 installed 29 multi-machine FMSs in Japan. At the same time, it is a medium volume producer of NCMTs, and may well be beginning to follow a \textit{system oriented cost leadership} strategy. Other machine oriented firms moving into FMS are Heller and Deckel in Germany and Ya-

\(^{16}\)In Appendix Table 1, we have on the basis of somewhat incomplete information listed market share data for the largest European, American, and Japanese firms for FMSs built around two or more NCMTs, i.e., excluding most systems around CNC lathes.

\(^{17}\)Four U.S. firms accounted for 18 percent taken jointly.

\(^{18}\)A few firms, with the same product portfolio, from Korea and Taiwan are beginning to compete with these Japanese firms (Jacobsson 1986, Jacobsson and Alam 1991).
mazaki, Okuma and Makino in Japan. Jointly, these firms (excluding Hitachi Seiki) had an accumulated eight percent market share of FMSs by 1988.

Several of the machine oriented firms thus appear to be attempting to move into the northeast square in Figure 3, i.e., combining system sales with an emphasis on relatively low price. Some firms (e.g., Deckel, Okuma, Makino, Mazak, and Hitachi Seiki) seem to be making this attempt by supplying smaller (2 to 4 machines) PLC controlled FMSs which are relatively "simple" and unintelligent, and which have an almost standardized design already.

Others are active in selling "intelligent" systems. These systems are controlled by a minicomputer (VAX) and, just recently, by PC (personal computer). Both Heller and Deckel are developing this type of business and several of the larger Japanese firms have sold very large systems, which presumably are not PLC controlled, on their home market. For instance, Yamazaki and Hitachi Seiki have an average of 8.4 and 6.8 machines, respectively, in their systems sold so far (calculated from IIASA [28]) which is greater than such firms as Mandelli, Comau, and Werner und Kolb. Furthermore, the Japanese firm Yamazaki, which is one of the largest machine tool firms in the world, is now also attempting to enter the European market for larger and intelligent systems.

Thus, what we are witnessing today are tentative steps eastward (in Figure 3) being taken by a number of firms which have hitherto been machine oriented. These firms are developing the FMS market with a range of different approaches, with Hitachi Seiki in the forefront. The bulk of the efforts appears to be directed towards the northeast square of Figure 3, i.e., through developing low cost systems. These steps are, however, not limited to the machine oriented cost leaders. It applies to a typical system oriented firm like Huller Hille. Even the market leader for intelligent systems, Werner und Kolb, has shown clear signs of trying to reach more price sensitive segments of the market by product innovations that reduce the price/performance ratio.

6. Dynamics of the FMS Industry

There is no reason to assume that the previous section portrays more than a static picture. In this section we will use our framework from section 2 to discuss some technical and economic trends that are judged to be vital for the future evolution of the FMS industry based on machining centers. We will then attempt to discuss how these trends may influence the technical and economic elements of industry structure and judge whether or not FMSs can form the basis for a sustainable revival of the European machine tool industry.

6.1 PRESENT TRENDS IN THE FMS INDUSTRY

As was mentioned in section 2, industrial evolution and the diffusion of a new substitute are shaped by a common set of driving forces. In the following paragraphs, we discuss our perception of what is taking place today in the industry supplying FMSs, in terms of these forces.

A number of significant product innovations have recently taken place. Changes in the adjacent computer industry has meant that PCs\(^{19}\) can be used to control intelligent systems. Both price and performance are improved. Price can be significantly lower as compared to using a minicomputer; according to industry sources the price for a PC-based system is 100,000 to 200,000 U.S. D lower (in 1989) compared to a system based

\(^{19}\)As PCs now have higher capacity, the operative system UNIX which is suitable for multi-task control, is available for PCs (not only for minicomputers like VAX).
TABLE 4
The Share of NCMTs and Other Components of Flexible Manufacturing Systems According to Different Sizes of FMSs

<table>
<thead>
<tr>
<th>Number of NCMTs</th>
<th>Total Costs (M U.S. $)</th>
<th>NCMTs (%)</th>
<th>Material Handling (%)</th>
<th>Information System (%)</th>
<th>Planning and Training (%)</th>
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<tr>
<td>2-4</td>
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<td>5-15</td>
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<tr>
<td>15-20</td>
<td>10-15</td>
<td>35-40</td>
<td>15</td>
<td>25-30</td>
<td>15-20</td>
</tr>
</tbody>
</table>

The number of observations is not given in the source.
Source: Ranta and Tchijov [30, p. 9].

on a VAX computer. In one important respect, performance is better vis-à-vis a solution based only on a PLC; a PLC controlled FMS has a closed computer architecture which makes the system very difficult to expand in terms of the number of machines it contains. This is a fundamental weakness for smaller and medium sized firms whose investment budget does not often allow for the procurement of more than one machine each year. Thus, for these firms, it is vital to be able to gradually build an FMS. This is now possible with the use of PCs for system control.

A second interesting product innovation is a new tool handling solution. The tools in the machines (which has tool storage integrated in the machine) need to be changed when other workpieces are to be machined or when the tools are worn out. The tool handling system has until recently been of two main types: 1) the tool is changed manually, and 2) the flexible manufacturing system has a central store from which a tool handling system (a robot) can supply the machine with a range of tools. This requires quite a large fixed investment. In order to reduce the investment costs, a third solution has recently been developed. The system is based on cassettes which are manually loaded/unloaded. These are then automatically transported to the machines by the same transportation system that is used for the work pieces, which is much cheaper than alternative 2 above. This is a particularly interesting solution for the price sensitive smaller and medium sized firms which need to change tools often.

The suppliers' experience is accumulating. This is important for two reasons. First, as the accumulated number of FMS installations increase, firms can systematize their experience into software and hardware modules for their systems. They can also build on their experience in the planning and educational phases. These two elements account today for a significant share of total costs, as is shown in Table 4. Thus, as experience accumulates, prices will probably come down significantly. Second, selling an FMS is a difficult task which requires a multi-disciplinary and highly experienced engineer. It is evident from many interviews that so far there has been a great shortage of such personnel. Naturally, this has meant that the supplying industry has favored sales to their traditional customers, often large firms. This supply capacity constraint is now being reduced, which increases the access of the new substitute for smaller and medium sized firms.

On the user side, there is a reduction in uncertainty as the teething problems are dealt with. This is, of course, an especially important consideration for smaller and medium sized users who cannot afford to have a large part of their production capacity out of use, and who do not have internal competence to deal with these teething problems.

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[20] For a longer discussion, see Carlsson and Jacobsson [2].
Furthermore, as the stock of FMSs grows, there will be an increasing number of installations to which customers can be referred, which decreases the uncertainty perceived by them.

There is a significant diffusion of proprietary knowledge in the system integration function. The machine oriented cost leaders are developing that capability which again increases the supply capacity of the industry.

Finally, the hitherto regional nature of the FMS market (see Appendix Table 1) is beginning to become global. In particular, entry of Japanese firms on the U.S. and European markets has started, although hesitantly and not always with initial success. Initially at least, the main emphasis of the Japanese firms lies in smaller, standardized systems, which is not surprising given their emphasis on sales to smaller and medium sized firms in the case of stand alone NCMTs.

To sum up, price/performance is going down generally speaking; a supply capacity is being built up for serving firms other than the larger ones and an emphasis is laid on developing FMSs to suit the demands of smaller and medium sized firms (lower costs, less uncertainty, open system architecture, alternative tool handling systems, etc.). Indeed, we are clearly seeing indications that the supplying industry is beginning to serve other buyer segments than those they have hitherto focused upon.

Evidence from the U.S., Italy, and Germany clearly shows that the present diffusion of FMSs is, at least by the end of the 1980s, largely restricted to larger firms, i.e., those with more than 500 employees, see Table 5 and Appendix Tables 2 and 3. In the U.S. for example (where the data probably also includes one machine system) only 18 percent of the surveyed firms using NCMTs in the employment size range of 20 to 99 used FMSs. For firms with more than 500 employees the figure rose to 51 percent.

However, in the U.S., these large companies with more than 500 employees had only 14% of the stock of CNC lathes and machining centers in 1989 (see Table 6). Thus 86% of the CNC lathes and machining centers were used in small and medium sized companies, firms which, so far, have only just begun to use FMSs. The potential use of FMSs in these smaller firms could, indeed, be very large.

This is not to say that all smaller companies could be included in the potential market for FMSs. For instance, they would need to have more than a couple of machining centers or CNC lathes to begin to consider installing an FMS but the discrepancy between the distribution by size of company of FMS and NCMTs is thought provoking. Indeed, taken jointly with the trends discussed above, we judge that it is highly plausible that this

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The success/failure seems to depend largely on the skills of their local distributors.

This applies to both multi-machine systems and systems built around a CNC lathe [19].
decade will see a race by companies into the northeast square in Figure 3 where they will supply (PC based) smaller and lower cost systems to smaller and medium sized firms on a large scale.

6.2 A REVIVAL FOR THE EUROPEAN MACHINE TOOL INDUSTRY?

In the course of this race, we judge that the FMS industry will change from regional to a global one. But will the globalization of the industry be associated with a revival of the European machine tool industry on the basis of system sales at the expense of the Japanese?

To be able to answer this question, we need to assess how the trends shaping industry evolution, described above, will affect the technical and economic elements forming industry structure. In particular, we need to be concerned with the character and height of the entry and mobility barriers into the FMS industry.

The companies at present in the southeast square of Figure 3, (with the exception of Huller Hille) specialize in supplying intelligent systems, i.e., they are system oriented differentiators. Being market leaders in intelligent systems means that they can benefit from economies of experience. primarily in the form of standardization of software and from reputation built up by their many reference installations (reducing the perceived risk of the customer). They have also built up impressive technological capabilities, in particular in system engineering and computer communication. These factors may seem to constitute formidable entry barriers for the machine oriented firms, in particular the Japanese, which in many cases have not even begun to sell FMSs in Europe.

We judge, however, that the system oriented differentiators will be under very considerable pressure in the years to come. In short, we believe that basing company strategy purely on leading the new technological discontinuity implies going for a position around which it is difficult to build significant and sustainable entry and mobility barriers. There are two reasons for this.

First, a lack of systems sales people, a lack of standardization of systems, and a hesitancy among the customers to buy FMSs has led to a slow diffusion of FMSs. This implies that the leading firms (in terms of number of units sold and product technology) have had problems in reaping substantial first mover advantages from their present superior system capability. In particular, creating a substantial barrier to entry in the form of relatively low prices (deriving from economies of scale and experience) has not been achieved.

Indeed, being small volume producers of machining centers means a cost disadvantage of considerable magnitude for these firms vis-à-vis most of the machine oriented cost leaders. The leading Japanese firms enjoy very significant economies of scale; volumes of output of the largest firms in Japan are many times that of the largest system oriented differentiator. There are also significant economies of scope for companies which are involved in the production of two or more of the following: stand alone NCMTs,

### TABLE 6

<table>
<thead>
<tr>
<th>Number of Employees</th>
<th>1-99</th>
<th>100-499</th>
<th>500+</th>
<th>Total</th>
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</thead>
<tbody>
<tr>
<td>NC lathes and machining centers (units)</td>
<td>78,331</td>
<td>31,049</td>
<td>17,746</td>
<td>127,126</td>
</tr>
<tr>
<td>Share (%)</td>
<td>62%</td>
<td>24%</td>
<td>14%</td>
<td>100%</td>
</tr>
</tbody>
</table>

*Source: Elaboration on American Machinist, November 1989, p. 105 [18].*
flexible transfer of lines, or FMSs. For the large Japanese machine oriented cost leaders, these economies arise as some costs are shared between CNC lathes and machining centers, both of which are produced by these firms. For example, the hardware and software of the CNC controllers for the two types of machine tools have great similarities. For the German machine oriented cost leaders who produce machining centers, FMSs, and flexible transfer lines (in particular Heller and Deckel), similar advantages arise in the product development phase. Both technical solutions and experience gained can be applied to all these products.

The cost disadvantage of the European system oriented differentiators in the production of machining centers is very important since the key cost component in the FMS is still the machine tool (see Table 4). Moreover, the share of the machine tools will increase as the cost of the information system and planning is reduced in the course of a learning process, where standardization is one of the main driving forces. Thus, as the machine oriented cost leaders move into the northeast square of Figure 3 and run down the experience curve for FMSs, their inherent cost advantage, arising from great economies of scale and scope, will lead to a superior cost position to that of the system oriented differentiators.

Second, although the system oriented differentiators have accumulated impressive technological capabilities they have not been able to erect substantial entry barriers in terms of technological capabilities. This is due to the nature of the technological change. In order to grasp the changes in the technology base we have, in Table 7, listed the major technologies in the machine tool industry for the period 1975 to 1990. Going back to the time of manual machine tools, the technology base of machine tool firms only included technologies from the generic field of mechanics—solid mechanics, machine design, and engineering materials. The shift to numerically controlled machine tools rendered the hitherto important area of gearing obsolete, since the movements of the tools were now carried out by electric motors that were controlled by a servo system. Moreover, control engineering and software engineering, coming from a different generic field, were added to the technology base. The technological change was therefore quite comprehensive in character; not only was a central technology made obsolete, but two additional technologies from a different generic area were added.

In spite of the apparent complexity of FMS, the nature of the technological change is less radical than in the previous case. No technology was made obsolete and the added technologies—system engineering and computer communication—build on the existing capabilities of the machine tool industry. Thus, in terms of technological capability, for those firms which mastered both advanced mechanical, control, and software engineering in the course of the first discontinuity, the technological barriers to FMSs are not overwhelming.

On the contrary, the technological resources of the Japanese and German machine oriented cost leaders are most impressive, both in terms of quantity, with 200 to 400 design engineers, and in terms of covering many engineering disciplines (mechanics, electronics, software, system integration).

Hence, the entry barriers are not very large for the machine oriented cost leaders

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23 It is important to note the difference between changes in the product and changes in the technology base. The product FMS differs a great deal from NCMTs, both in terms of how it works and in terms of performance, but the technology base (the technical competence) needed for designing and producing an FMS and an NCMT are very much the same, as discussed above.

24 Application engineering is critical knowledge here.
<table>
<thead>
<tr>
<th></th>
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<th></th>
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<td>FMS—1990</td>
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<td>X</td>
<td>X</td>
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<td>X</td>
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</tbody>
</table>

<sup>a</sup>Includes knowledge of drives, sensors, and electronics.

<sup>b</sup>Application specific knowledge is a prerequisite for good system engineering.

*Source*: Based on interview with Professor Nils Mårtensson, Chalmers University of Technology (July, 1991) by E. Ehnberg and S. Jacobsson.
into the FMS field, neither in terms of cost nor in terms of technological capabilities and, indeed, they may even soon have acquired a cost advantage. All this points, in our minds, to a continuing dominance of the machine tool industry by the existing machine oriented cost leaders. These are mainly Japanese, so a revival of the European machine tool industry with the help of FMSs is not likely to happen. However, the occasional European firm, in particular Heller, which is the only European volume producer of machining centers, may stand a good chance in the FMS industry of the 1990s.

7. Concluding Remarks

Looking at the machine tool industry on a global basis, dramatic changes in the competitive strength of firms and countries have taken place in the past 15 years. A few Japanese, German, and Italian firms have come to dominate the previously fragmented machine tool industry.

The technological discontinuity from stand alone NCMTs to FMSs will probably, in our view, only continue this process of concentration. Those, primarily European, firms which have achieved a strong competitive position on the basis of system sales are likely to be subjected to an increasing competitive pressure from the large, close to oligopolistic, firms which so far have been basically machine oriented. These firms are not expected to lose their market position permanently in conjunction with the technological discontinuity to FMS but will draw on their existing technological capabilities and superior cost structure to break into the FMS market on a large scale in the 1990s.

The question which then arises is: what explains the widely different effects on the competitive positions of firms and nations of these two technological discontinuities? In other words, when are technological discontinuities disruptive? While we have no ambition to provide a complete answer, a few observations from our two cases may be warranted.

The nature of the change of the technology base presumably matters. We have suggested that the technological discontinuity from NCMTs to FMSs was less "radical" than that from conventional machine tools to NCMTs in that the latter involved both a destruction of capabilities and the adding of new technologies from a distinct generic area to the base. The former discontinuity involved greater cumulative elements. This difference has two implications. First, the ability of firms to see the opportunities associated with the new substitute, and then be able to act on it strategically, is presumably more evenly distributed the closer the technology base of the new substitute is to the one it is intended to replace. Thus, it is less likely that one or a few firms can gain decisive first mover advantages. Second, the more cumulative the technological change is, the less likely it is for first movers to come to benefit from substantial technological entry barriers.

The rate of diffusion, or substitution, is presumably a second critical factor. If the rate of diffusion is slow, latecomers are given time to detect the new opportunities and act strategically on them, before the early movers have erected significant entry barriers. With a fast rate of diffusion, first movers can more easily build sustainable entry barriers in the form of economies of scale and experience economies, closed distribution networks, etc., before the other firms have reacted on the new strategic opportunity.

As noted above, these observations can only be highly preliminary. Our empirical and conceptual knowledge is inadequate to both understand and, especially, predict how and under what conditions technological change will affect the structure of and nature of competition in an industry. It would therefore seem important, from the point of view of both management and Government policy makers, to examine more closely and sys-
tematically the interaction between technological discontinuities and economic performance of firms, and indeed, of nations.

References
34. Werner und Kolb, interview with the company (1989).
35. Heller, interview with the company (1989).
36. Huller Hille, interview with the company (1989).
38. Sajo, interview with the company (1990).
41. Tecnologie Meccaniche, Le Prime 200, no. 5 1989 (a list of the 200 largest machine tool producers in Italy in terms of turnover) (1989).
42. The U.S. Department of Commerce, Information received on a private basis (1989).

Received 5 August, 1991; revised 28 April, 1992.

**APPENDIX TABLE 1**

<table>
<thead>
<tr>
<th>Company</th>
<th>Europe (No.)</th>
<th>U.S.* (No.)</th>
<th>Japan* (No.)</th>
<th>Total (No.)</th>
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<tr>
<td>European companies:</td>
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### APPENDIX TABLE 1
Continued

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<td><strong>Total</strong></td>
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<td>97</td>
<td>117</td>
<td>620</td>
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*The U.S. includes Canada. Japan includes Taiwan, Korea and China.

Sources: For each company (except Werner und Kolb and Huller Hille) the source [33] or FMS World Data Bank [28] with most notations was used. a [33]. b [28]. c Source for sales to Europe: [33]; source for sales to the U.S. and Japan: [28]. d Estimate based upon interview with the company (1989 for Huller Hille [36], 1990 for SMT [43] and Sajo [38]). e Elaboration based on [44]. In the source the total number of installations is said to be 81. Out of these the geographic location is only given for 73. The remaining 8 installations are assumed to have the same pattern of geographical location as the 73.

### APPENDIX TABLE 2
Firms using FMSs by number of employees (Italy, 1988)

<table>
<thead>
<tr>
<th>Employment size</th>
<th>2–3 NCMTs</th>
<th>&gt; 3 NCMTs</th>
<th>All sizes</th>
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<td>20–49</td>
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<tr>
<td>50–199</td>
<td>30.2%</td>
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<td>23%</td>
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<td>200–499</td>
<td>32.6%</td>
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<td>&gt;500</td>
<td>37.2%</td>
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<td>49%</td>
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<td><strong>Total</strong></td>
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<td>100.0%b</td>
<td>100%</td>
</tr>
</tbody>
</table>

*44 installations
*b25 installations

Source: [45]
APPENDIX Table 3

Percent of establishments that use NCMTs and FMSs, by employment size (FRG 1989)

<table>
<thead>
<tr>
<th>Employment size</th>
<th>1-19</th>
<th>20-49</th>
<th>50-99</th>
<th>100-199</th>
<th>200-499</th>
<th>300-999</th>
</tr>
</thead>
<tbody>
<tr>
<td>FMS&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0%</td>
<td>1%</td>
<td>3%</td>
<td>1%</td>
<td>9%</td>
<td>20%</td>
</tr>
<tr>
<td>NCMTs</td>
<td>8%</td>
<td>27%</td>
<td>40%</td>
<td>56%</td>
<td>57%</td>
<td>81%</td>
</tr>
<tr>
<td>Percent of NCMT using FMS&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.0%</td>
<td>3.7%</td>
<td>7.5%</td>
<td>1.8%</td>
<td>15.8%</td>
<td>24.7%</td>
</tr>
</tbody>
</table>

<sup>a</sup>FMS might include 1-machine systems.

<sup>b</sup>Assuming that no FMS is used by an est. without NCMTs.

Source: Elaboration on data in [31].