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Trends and perspectives in flexible and reconfigurable manufacturing systems

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Flexible manufacturing systems (FMS) - reconfigurable manufacturing systems (RMS) - CNC machine tools - modular machines - and open architecture systems

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Abstract

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Keywords: Flexible manufacturing systems (FMS), reconfigurable machining systems (RMS), CNC machine tools, modular machines, and open architecture systems.

1. Introduction

Unprecedented and abrupt changes in market demands represent new conditions that manufacturers of consumer goods needed to operate within. Several factors are simultaneously contributing to these market changes, including globalization of the economy, saturated market and rapid advances made in process technology. The result has been fragmentation of the market (size and time), and shorter product cycles. Therefore, higher quality products at lower cost become necessary, and timely response to market changes becomes the competitive advantage. This in turn requires appropriate business strategies and appropriate manufacturing technologies.

Each major manufacturing paradigm has tried to address a particular aspect of manufacturing (*Buzacott, 1995; Kusiak and He, 1997; Ashley, 1997; Sanchez, 1996*). In *mass production* dedicated lines were designed for production of a specific part. It uses transfer line technology with fixed tooling and automation. Its objective is to cost-effectively produce one specific part type at high volumes and the required quality. *Lean manufacturing* was introduced to efficiently eliminate waste, reduce cost, and improve quality. By many (*Sheridan, 1993; Noaker, 1994; Bjorkman, 1996*), lean manufacturing is considered to be an enhancement of mass production (i.e., not a new technique). Its objectives are to maximize profit by reducing costs, waste of material, etc. These are essentially the underlying principles of mass production. *Flexible manufacturing* systems (FMS) address changes in work orders, production schedules, part-programs, and tooling for production of a family of parts. As reported by (*Mansfield, 1993; Jaikumar, 1986; Ito, 1988; Ayres et al., 1992*), the rate of diffusion of FMSs in the US industry was fairly slow, especially when it was introduced to the market. While it achieved some acceptance in Europe and Japan, it was not very successful in the US. There are different views on the causes of this (*Graham, 1988; Jaikumar, 1986*). Perhaps substantial average estimated rate of return from all investments in FMS is the most important reason, while complexity, lack of reliability of the software, the needs for highly skilled personnel, and supports costs might contribute as well. In terms of design, FMS possess an integral architecture (hardware/software) meaning that the boundaries between the components and their functionalities are often difficult to identify and they are tightly linked together. Furthermore, it has fixed hardware and fixed (but programmable) software. This type of architecture does not allow changes to be made. Therefore, FMS has limited capabilities in terms of upgrading, add-ons, customization and changes in production capacity. *Agile manufacturing* (*Goldman, Nagel, and Preiss, 1995*) was introduced as a new approach to respond to rapid change due to competition. It focuses on organizational aspects of a manufacturing enterprise and brings together individual companies to form an enterprise of manufacturers and their suppliers linked via advanced networks of computers and communication systems. Agile manufacturing, however, does not deal with the production system technology or operations.

More recently, the *reconfigurable manufacturing* system concept was introduced (*Koren and Ulsoy, 1997; Mehrabi and Ulsoy, 1997; Koren et al., 1999*) to respond to this new market oriented manufacturing environment. In terms of design, RMS has a modular structure (software and hardware) that allows ease of reconfiguration as a strategy to adopt to market demands. Modular machines and open-architecture controllers are the key enabling technologies for RMS, and have the ability to integrate/remove new software/hardware modules without affecting the rest of the system. This offers RMS the ability to be converted quickly to the production of new models, to be adjusted to exact capacity requirements quickly as market grows and product changes, and to be able to integrate new technology (*Bollinger and Rusnak, 1998; National Research Council Report, 1998*).

A survey of the literature suggests that there are several recent studies on various issues in future manufacturing and machine tools (*NGM Report, 1997; AMT Report, 1996; NRC Report, 1998; Rand Report, 1997; J. Lee, 1997*). Next Generation Manufacturing Project (*NGM Report, 1998*) has carried out a comprehensive study of the imperatives of future manufacturing among many other issues. In this regard, some of the important drivers of the next generation manufacturing environment are identified and the attributes required to respond to these drivers are defined. Accordingly, responsiveness of manufacturing firms plays a critical role in their success in the new challenges of global competitiveness. As reported, development and implementation of reconfigurable, scalable manufacturing processes are important preliminary steps in achieving production systems responsiveness. Also, important roles of responsive information systems and rapid product/process realization are mentioned among the other imperatives of future manufacturing. The same views are supported by the results of another study carried out by the National Research Council (*NRC Report, 1999).* In their report on a Delphi study of Manufacturing 2020, the RMS concept was identified as the number one priority technology for future manufacturing, and one of six key research challenges.

In an effort to better understand current and future needs in manufacturing and their enabling technology, a survey of experts in manufacturing was conducted by the Engineering Research Center for Reconfigurable Machining Systems (ERC/RMS) during 1997 *(Heytler and Ulsoy, 1998).* The survey tries to explain the experiences to date with flexible manufacturing systems and identifies their accomplishments and failure. It also addresses the possible ways reconfigurable manufacturing systems address some of the needs of modern manufacturing. This article summarizes the key results from that survey.

2. Objectives of the survey

The survey questionnaire was specifically designed to: (i) obtain a current assessment of flexible machining systems, (ii) identify the potential benefits of, and key enabling technologies needed for, reconfigurable machining systems.

The panelists (i.e., survey respondents) were given the following definitions:

Flexible Manufacturing System (FMS): A programmable machining system configuration which incorporates software to handle changes in work orders, production schedules, part-programs, and tooling for several families of parts.

The objective of a FMS is to make possible the manufacture of several families of parts, with shortened changeover time, on the same system.

Reconfigurable Machining System (RMS): A machining system which can be created by incorporating basic process modules — both hardware and software — that can be rearranged or replaced quickly and reliably. Reconfiguration allows adding, removing, or modifying specific process capabilities, controls, software, or machine structure to adjust production capacity in response to changing market demands or technologies. This type of system provides customized flexibility for a particular part-family, and will be open-ended, so that it can be improved, upgraded, and reconfigured, rather than replaced.

The objective of an RMS is to provide exactly the functionality and capacity that is needed, exactly when it is needed. RMS goes beyond the objectives of FMS by permitting: (1) reduction of lead time for launching new systems and reconfiguring existing systems, and (2) the rapid modification and quick integration of new technology and/or new functions into existing systems.

More detailed explanation of the characteristics and definition of reconfigurable manufacturing systems are given in (*Koren and Ulsoy, 1997; Bollinger and Rusnak, 1998; Mehrabi and Ulsoy, 1997; Mehrabi et al. 2000*). In essence, a reconfigurable manufacturing system aims to be installed with the exact production capacity and functionality needed, and may be upgraded when needed. Also, expanded functionality enables the production of more complex part types and the production of a variety of part types on the same system; it will be associated with adding process capabilities, auxiliary devices, more axis motions, larger tool magazines and enhanced controllers (*Koren and Ulsoy, 1997; Mehrabi and Ulsoy, 1997*).

The respondents to the questionnaire (total of 66) were divided almost evenly between flexible machining system users and builders (the latter including component suppliers; see Table 1). The panelists were experts (i.e., president or vice-president, director, general manager, manager, engineer, specialists, consultant, etc.) in manufacturing systems covering a large scope of industries including machine tool builders/users, control builders/users, automotive manufacturers, software developers and “Others” (e.g., research institutes, trade associations, the US Government, and non-FMS-using firms) (see Table 2). Among the users who responded to the survey (%47 of the respondents; see Table 1), %67 were the end users of FMSs and %33 were responsible for specifying and installing them (*Heytler and Ulsoy, 1998*). Therefore, this variety in the scope of the participants make the data rich enough to draw some useful conclusions.

Respondents	Number of Responses	Percent of Responses
Flexible Manufacturing System users	**31**	**47%**
Flexible Manufacturing System builders	**24**	**36%**
Suppliers of Flexible Machining System components	4	6%
Educational Institutions	1	2%
Others	6	9%

Table 1. Distribution of the respondents by type of organization.

Type of Industry Respondents	**No. of Responses**	**Percent of Responses**
Machine Tool Builder	26	40%
Automotive	13	20%
Automotive Supplier	7	11%
Machinery	3	5%
Industrial Components	3	5%
Aerospace	2	3%
FMS Equip. Builder	2	3%
Earth Moving Equip.	2	3%
Research Institute	2	3%
Robotics	1	1%
Oil Tools	1	1%
Mining Equip.	1	1%
FMS Components	1	1%
Trade Association	1	1%
US Government	1	1%
TOTAL RESPONSES	**66**	**100%**

Table 2. Respondents and their industries.

3. Experience to Date with FMS (Review of the Results)

This section of the paper deals with user experiences with flexible manufacturing systems (FMS). It includes brief explanations of the responses received from the panelists and analysis of the results. It first summarizes general information regarding distribution of the data collected (i.e., respondents, production volume, and the type of FMS being used). Then, the key findings regarding FMS such as motives behind purchasing FMS, user expectation and satisfaction and future forecast will be discussed.

3.1 General Description of FMS Being Reported

Size of the manufacturing systems: The distribution of the respondents depicted a comparatively smooth distribution of FMS size between two and ten stations. Combined with other data, it appears that for most manufacturing applications, 10 stations or fewer seem to be adequate. This perhaps leads to another important conclusion: the industry does not have extensive experience with FMSs that include more than 10 stations. This is compatible with reports on recent failure of large FMSs. Also, from the data no correlation was found whatsoever regarding the size of a given FMS (as measured by number of stations) and industry type.

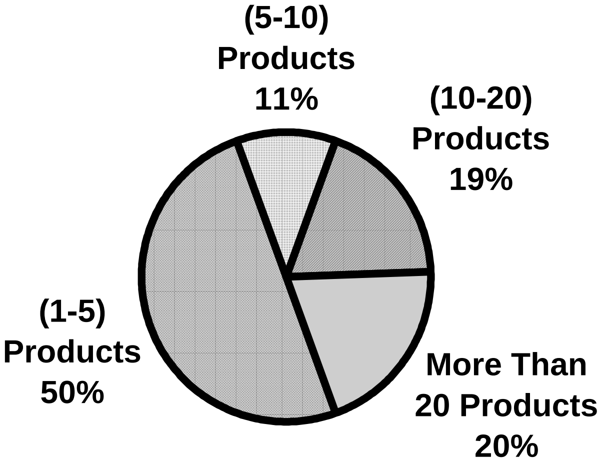
Annual production rate: The results show that over 60 percent of respondents reported their company's FMS production level as falling between 25,000 and 500,000 annually, with a distinct peak in the 50,000 to 100,000 units per year range – typical of firms in many industries. The data reinforce the finding that FMS units have been installed in a wide variety of applications to perform a wide variety of functions, and thus yield a wide variety of results.

Characteristic production tolerances reported by panel members range from a low of ±.0025 mm (±.0001 inch) to a high of ±2mm (±.08 inch). Almost half of the respondents (45 percent) operate their FMS at within a range of ±.0005 and ±.001 inch; another 30 percent operate between ±.02 and ±.05 inch. No strong correlation was found between tolerance levels and specific industries represented by the panel.

3.2 Motives for Investing in FMS

Specific motives for investing in FMS technology varied among panel members. A significant majority (80 percent) responded that their systems were purchased to manufacture existing products, while 63 percent said the systems would be used for future product lines; given that respondents could provide more than one answer, 15 individuals (30 percent) indicated that the FMS would be used for both purposes. Finally, 20 percent indicated that the equipment would also be put to use manufacturing prototypes, although none stated that the machinery would be dedicated solely to this purpose.

One of the surprises in analyzing the data is that only 22 percent handle what might be termed a wide variety of products (more than 20 on the same line). By contrast, almost 50 percent of the respondents (see Figure 1) confirmed that they handle a total of 5 or fewer different end products (of the same family) on the same line (i.e., the use of FMS for comparatively part-family dedicated production). Since the production of small quantities of a variety of items is considered the primary strength of FMS technology, its use for comparatively dedicated production would appear unnecessary and expensive. This is consistent with the results of previous studies (*Jaikumar, 1986; Mansfield, 1993*) that product variety in US FMSs is relatively low as compared to Japanese FMS. The implication of the results is that essentially, some of the manufacturers did not need the flexibility and extra functionality that came with the FMSs when they bought them. But, they had to buy FMS because they did not have any other alternative.



It is the opinion of the authors that for some important applications a system is needed with more features than dedicated transfer lines (to deliver a limited variety of products of the same family) but not the general flexibility of an FMS. RMS technology (see Figure 2) provides a system that can accommodate the necessary trade-offs between capacity and functionality, and as in many cases occupy a middle ground between dedicated transfer lines and FMSs. The important feature of RMS is that its location in the capacity-functionality space can change over time.

Figure 1. Distribution of FMS by number of products

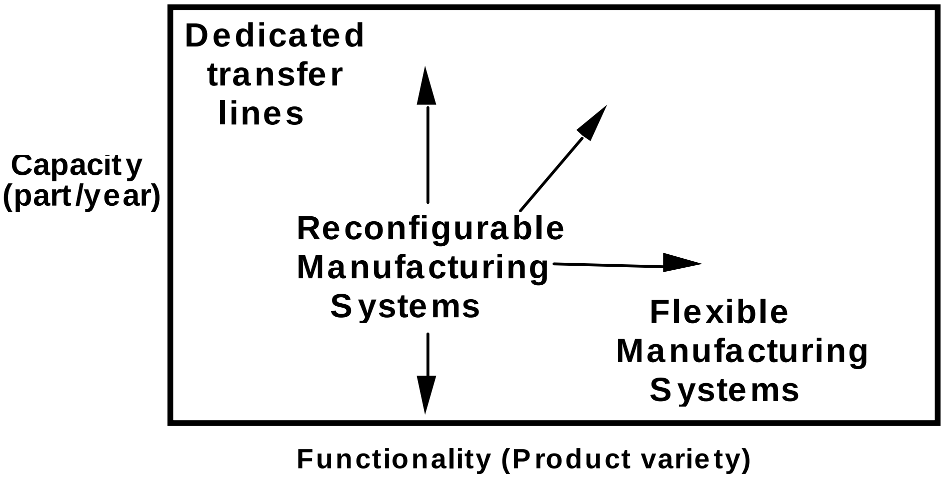


Figure 2. Conceptual mapping several types of manufacturing systems (i.e., dedicated, flexible, and reconfigurable) in the Capacity-Functionality plane.

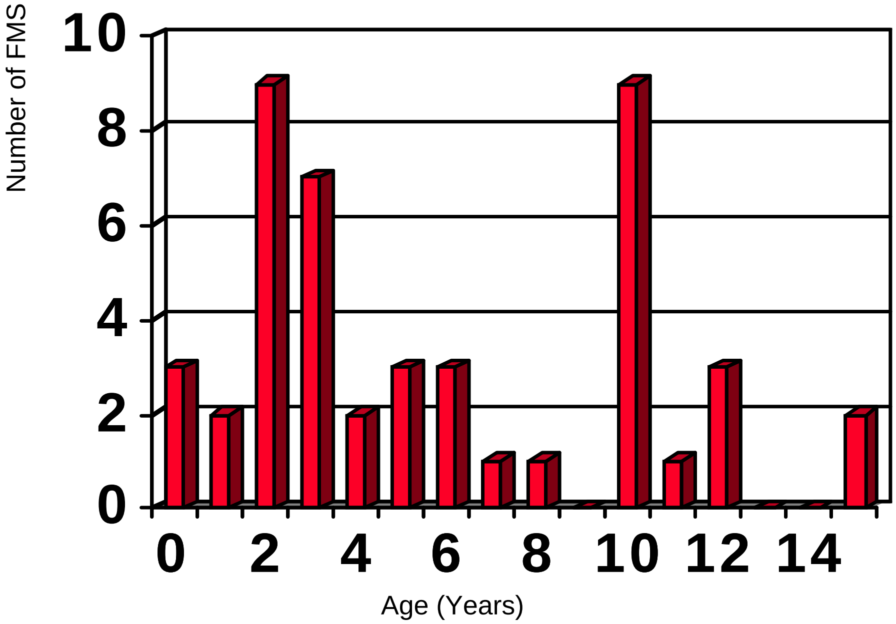


Figure 3. Distribution of FMS by age of System

FMS Age: The distribution of the ages of FMS as represented by the population of this study is distinctly bimodal. One peak appears in the range of 2-3 years, with a second around 10 years, and a relatively sharp decline in between (see Figure 3). This phenomenon reflects the fact that current market conditions (i.e., within last 5-6 years) are demanding a variety of products and manufacturers are responding by purchasing FMS. But, is FMS the proper manufacturing system to meet these needs? The answer becomes more clear when the rest of the results are reviewed.

The reason for the peak at 10 years of age in application of FMSs could be the fact that (although FMSs were introduced in the late 70’s) it was only in the late 80’s that they were widely used by industry. When they were implemented (in the late 1980’s), the market really demanded a relatively limited variety in products (within the same product family). Probably, such demands could be met with a manufacturing system like a dedicated transfer line (with significantly lower cost) with some limited flexibility. Since such a system did not exist, the industry used FMS which was an expensive option when compared to the cost of a dedicated transfer line. Also, manufacturers were not confident because it was a new technology. Therefore, FMS was not operating at its full potential (i.e., delivery of product variety) while at the same time it was also relatively expensive; this could be among the reasons that made FMS unattractive as can be observed from the results.

Existing vs. Future Products: A majority (around 80 percent) of the panelists indicated that they purchased FMS for manufacture of existing products and 63 percent (multiple answers permitted) said that FMS was purchased for possible manufacture of future products. Also, more than 61 percent of the respondent reported that they deliberately purchased more production capacity than needed to permit possible future expansion (see Table 3).

This is a clear indication of the fact that flexible systems are built with all the flexibility, functionality, and capacity available, even, as in some cases, with those that may not be needed at installation time. The logic behind this could be that "to buy it just in case it may one day be needed." However, in these cases capital lies idle on the shop floor and a major portion of the capital investment is wasted. The vital role of RMS technology, as a system that can rapidly respond to a required capacity and functionality, is evident from this result.

3.3 User Satisfaction with FMS

Panel members affiliated with organizations operating FMS were provided the opportunity to rate their satisfaction with the performance of their systems compared to their previous means of production on the basis of 16 criteria (e.g., investment cost reduction, throughput, ramp-up time for a new product, time required for product changeovers, etc.). In all cases, the median rankings indicated either mild satisfaction or complete neutrality; in no instance did an unsatisfactory median ranking appear. Those factors earning a "mild satisfaction" rating included throughput, increased product variety, time required for product changeovers, ramp-up time for new products, product quality, repeatability, lead time for introduction of a new function or technology into the the system, overall ease of introduction of a new process technology, uptime, and amount of product rework needed. "Neutral" ratings were given to investment cost reduction, system lifetime, reduced maintenance, reduced floor space required, use for prototype development, and adjustments to capacity. When asked whether their FMS continued to be used for the originally intended applications, 87 percent of respondents answered "Yes." Four percent reported that their FMS had been removed from production, while the remaining 9 percent reported that their systems had been shifted to substantially different applications, generally within the first 18 months of operation.

RESPONDENTS	**Number of "Yes" Responses**	**Percent of "Yes" Responses**
Manufacture of existing products	45	80%
Manufacture of products that are planned, but not yet in production	35	63%
Manufacture of prototypes	11	20%
Did you purchase more production capacity than needed deliberately to permit for future expansion?	33	61%

** Multiple answers permitted.

Table 3. Reasons behind purchase of FMS.

Another set of questions examined whether panel members believed their FMSs were being operated close to their full potential. Surprisingly, less than half (47 percent) agreed that they were. Of the remainder, half reported that their systems are being run at less than 65 percent of full potential; 17 percent estimated the figure at under 50 percent of potential. This result would appear to belie earlier responses of satisfaction with the performance of FMS. The figures become even more pessimistic when applied to FMS in all of industry rather than simply specific companies. Fully two-thirds of respondents stated that they did not believe that FMS is living up to its promise across all manufacturing. This outcome is somewhat puzzling in light of the earlier findings regarding individual user satisfaction, and to the plans to purchase FMS. The results show that despite reports of suboptimal performance, and some degree of discontent with their performance, the results achieved by these systems has warranted their continued operation.

Finally, panelists were asked to identify what they believed were the major shortcomings or limitations to current FMS technology, and the likelihood that each might be resolved by the year 2000. As expected, a long list of highly varied responses was provided to this open-ended question. Among the areas seen as least tractable to quick resolution were initial investment cost, flexible tooling and fixturing, system flexibility, scheduling issues, and – perhaps most important – training. At the other end of the scale, many software and programming issues were seen as likely to be taken care of in the near future, as were many material handling, compatibility, maintenance, and miscellaneous hardware problems. Overall, despite the long list of limitations and the view that the technology still hasn’t lived up to its full potential, the panel clearly intends to continue investing in FMS technology.

3.4 Expected Versus Actual Performance of FMS

Panelists were asked to describe their expectations of FMS performance as measured by eleven key criteria. They were then asked about their actual experiences immediately after installation of the equipment, and two years later, presumably after most of the major problems inherent in any new system were worked out.

Somewhat surprisingly, most of the expectations reported were comparatively modest, given all the fanfare frequently accompanying FMS. However, as a result of these realistic expectations, the new systems tended to meet, or in some cases even exceed, most of the performance targets within two years.

Among the criteria examined were ramp-up time after installation of the FMS and ramp-up time for the addition of a new product into the production mix. In both cases, the performance failed to meet expectations for many panelists. The median new system ramp-up time came in at 9 months, or 50 percent above the median target of 6 months. For new product ramp-up, median actual time after two years remained 100 percent higher, at 2 months versus 1 month planned.

However, the median amount of time required to prepare the system for the inclusion of a new product remained steady right at the projected level of 3 months. The reported median changeover time between lot runs actually came out better than anticipated after two years, at 30 seconds compared to the goal of one minute. And the median number of products per FMS came to 22, well above the mark of 14.

Median overall uptime understandably suffered at the time of FMS introduction while the system was debugged; however, by the end of two years, it had risen to meet the goal of 85 percent. However, when compared to previous production technologies, FMS users reported no significant changes in either scheduled maintenance downtime or unplanned downtime, in both cases meeting expectations.

Staffing levels were also examined. Operator levels hit the median target of 4 per system. However, while there was no change in median required levels of support and maintenance labor or production labor compared to pre-FMS levels, there was a median goal of a 25 percent reduction in production labor that went unfulfilled.

3.5 Forecasts and Plans for the Future

Over 60 percent of the panelists reported that at the time of the initial FMS purchase, more production capacity was installed than was needed at the time. This was apparently done in order to accommodate expansion in production requirements. Of these, almost 90 percent reported that this excess capacity had been substantially or completely utilized. There was no correlation found between these 90 percent and overall annual production.

Similarly, 55 percent of panel members reported that more FMS features were purchased than were required at the time of installation. Of those, most still had unused capabilities. However, almost half of the reported idle features were excess tool magazine capacity.

Almost half (%48) of the respondents predicted their company's purchase of additional FMS capacity as a means to supplement existing non-FMS production, while 25 percent expected additional investment in FMS in order to supplement existing FMS production. These results clearly show that the majority of manufacturers (around %73) are looking for a system that could accommodate incremental increase in capacity of their existing production system (FMS/non-FMS) while they do not need the extra functionality delivered by FMS. This is a clear indication of the critical role that RMSs can play (both as a supplement to the existing systems to compensate for the required capacity/functionality or by its own) in modern manufacturing.

4. The Future of Flexible Machining: RMS (Review of Results)

The panelists were presented with a set of questions regarding the specific aspects of RMSs and their potential impacts on future manufacturing. Also, the panelists were asked to give their views on certain key enabling technologies in order to identify which area of research need more attention.

The overall results indicate that panelist agree that RMS inherently has the potential to address some of the shortcoming of FMS. However, the panelists emphasized that certain key technologies such as modular machines and open architecture control systems must be developed for RMS to be realized. Specific data and analyses of the results of each question can be found in the following subsections. This is very consistent with the recent National Research Council Report (NRC, 1998) that identified RMS as both number one priority technology for manufacturing in the year 2020, as well as one of six grand challenges where research efforts need to be focused.

4.1 Perspectives in Flexible and Reconfigurable Manufacturing Systems

Panel members were asked to provide their views in various categories on the promise of RMS as a next step in the evolution of production technology. The RMS was given median ratings of “strong promise” for easier changes in production capacity, increasing product variety, reduced time for product changeovers, reduced ramp-up time for new products, and system lifetime costs (see table 4). Median ratings of “moderate promise” were also assigned to investment cost reduction, throughput, reduced maintenance, increased product quality, increased uptime, and easier prototype development. Only “slight promise” was seen for reduced floor space requirements. Another open-ended question, this one regarding their expectations of key advantages to be held by RMSs, was also put to the panel. As expected, the diversity of responses was large. Nevertheless, several major recurring themes were uncovered from the data. These included lower costs (both system and tooling), ease of changing equipment configuration,

	Mean Value	**Median response**	**Interquartile Range**
Cost Factors:			
Investment cost reduction	3.1	3	2/4
Lifetime of the system	3.6	4	¾
Throughput	3.2	3	¾
Reduced maintenance	2.8	3	2/3
Reduction in floor space	2.8	2	2/3
Increased ease in changes in production capacity	3.8	4	¾
Other factors:			
Increased product quality	3.0	3	2/4
Increased product variety	3.9	4	3/4
Reduced time required for product changeover	3.8	4	3/5
Reduced ramp-up time for a new product	3.7	4	¾
Increased uptime	3.0	3	2/4
Enhanced ease of prototype development	3.0	3	2/3

*Note: Interquartile range (IRQ) is indicator of the degree of diversity of opinion (i.e., the inverse of consensus) among panelists. Thus, under the condition of extensive or complete unanimity, the IQR values will be identical.

Table 4. Promise of RMSs to improve performance.

faster product changeover and new product ramp-up, ease of introduction of a new function or process technology, and greater product variety.

It is clear that the panel sees RMS as a desirable next step in the evolution of production technology. They list a host of potential benefits associated with its development, and rate these benefits as significant.

4.2 Potential Enabling Technologies

Various technologies, processes, and other factors may be employed as part of the operation of Reconfigurable Machining Systems. Some are more generally useful than others, and scarce development resources should be directed toward those with wider potential applications. In order to help determine which areas should receive more immediate attention, panel members were asked to give their views on the importance of a number of technologies, process, and other factors.

Five items listed received median ratings of "extremely important". These include high-speed machining (process), modular machine tools (technology), open architecture systems (methods), training of operators, and education of engineers (education). Fifteen factors were deemed "moderately important"; these included mostly mechanical component (such as material handling technologies, linear drives, etc.), software/hardware enhancements (e.g., machine self-diagnosis, PC-based controllers, adaptive control and predictive maintenance), and machining processes (specifically, dry and parallel machining). The panel was asked to answer in depth questions regarding two specific aspects of RMS, modular machine tools and open-architecture control systems (OACs). With regard to the former, the panel uniformly rated all the performance criteria provided as "moderately important" for the success of modular machine tools. These criteria included system design time, machine installation, ease of adding new features, ease of upgrading technology, part quality and accuracy, the ability to customize system features, multifunctionality, and, finally, cost. With regard to OACs, the panel sees only limited application today, but fairly widespread by 2005.

The effect of the presence of OACs on future modular machine tool sales was also probed. At first glance, the result was mildly surprising: The panel forecast that significant improvements in OAC technology would lead to only somewhat accelerated sales of modular machine tools. However, when it is remembered that modular machine tool technology was earlier rated as “extremely important,” it seems reasonable to conclude that sales of these tools will be strong regardless of the presence of better-developed open-architecture controllers. That is not to say that powerful OACs will not be desirable, or that their presence won’t add to the effectiveness, and hence appeal, of modular machine tools. However, the marginal effect of OACs on modular tool sales, given expectations of already high sale rates, can be expected to be muted.

Finally, a question directed at material handling systems was brought before the panel. This question asked about the mechanical suitability and cost-effectiveness of three technologies – non-wire automated guided vehicles, gantry robots, and conventional conveyors – for RMS applications. In each case, the panel gave a median response of only “adequate.” From the comments to the question, it appears that AGVs, and possibly robots, are seen as too complex for the task, and that each could represent a bottleneck in the production process. Although no details regarding conveyors were provided, several panelists suggested their own alternative, development of a material handling component that would be integral to the RMS itself, rather than an external add-on feature.

4.3 Software issues

To this panel, software issues probably represented the single area of greatest concern for the successful development of Reconfigurable Machining System technology. In order to identify priorities regarding RMS-related software development, panelists were asked to rank-order the importance of various potential software tools. These tools included software to configure: process and tooling; machine selection, layout, and process planning; machines from available modules; machine tool controllers from available control modules; and system-level factory communication software. Unfortunately, when asked to rank-order the usefulness of these five software tools for use in RMS, the results were scattered, and no consensus could be discerned.

Respondents were also given an open-ended question regarding key software issues that need to be resolved by 2005 in order to enable the goals of RMS to be met. As with other open-ended questions, the panel supplied a surfeit of responses. However, when these responses were categorized, a handful stood out as having fairly widespread concern. The single most-often mentioned topic was automated self-diagnosis and self-correction, mentioned by 11 of the 54 individuals responding to this question. The next largest grouping of responses was modularity of software elements. User friendliness and standardization of software elements also found frequent mention. This last response was buttressed by two other related ones, system compatibility between different suppliers and communications among equipment. The remainder of the issues identified by panel members were scattered among a score of other topics.

5. Summary of Results

This report documents the results of a survey conducted by the Engineering Research Center for Reconfigurable Machining Systems (ERC/RMS) during 1997 (*Heytler and Ulsoy, 1998*). A panel of experts in manufacturing systems were asked to assess:

- The current state of flexible manufacturing systems (FMS);
- The potential role for, and the key enabling technologies needed to realize, reconfigurable manufacturing systems (RMS).

The survey instrument was designed with the assistance of the ERC/RMS Design & Integration Team, and sent to the experts in industry. The responses received led to the following main results:

(i) The main results regarding FMS included:

- Fully two thirds of respondents stated that FMS is not living up to its full potential.

- Well over half reported purchasing FMS with excess capacity (which was eventually used) and excess features (which in many cases were not eventually used).
- Respondents identified a variety of problems associated with FMS, including training, reconfigurability, reliability & maintenance, software & communications, and cost.
- Despite these issues, approximately 75% of respondents said they will purchase additional, or expand existing, FMS.

(ii) The main results regarding RMS included:

- Respondents clearly agree that RMS is a desirable next step in the evolution of production systems.
- Key technologies needed for RMS were identified, and include training & education, high speed machining, modular machines, and open-architecture controls.

6. Interpretation of Results

This survey was conducted to assess the experience with the use of FMSs in industry and to examine different aspects of RMSs as a possible solution to some of the shortcomings of FMSs. From the survey results, it appears that FMSs have excess capacity and features which in many cases were not eventually used. Furthermore, their complexity, high initial costs, lack of reliability of the software, the needs for highly skilled personnel and support costs, and lack of capability and willingness of machine tool builders to carry out necessary system engineering involved are among the reasons that make FMSs not very attractive to industry. The basic components of FMSs (e.g., computer numerically controlled (CNC) machines, robots, and other programmable automation) have a fixed hardware and fixed software. Thus, integration of new machines/components and software becomes very difficult, if not impossible. Therefore, upgrading and adding incremental capacity is an issue with FMSs. From the responses, it seems industry is looking for a system that is less complex in nature and more adaptable to changing needs in terms of capacity and gradual changes in functionality. RMSs can be a solution to part of this problem by noting that its components have modular structure and the control software that is running the entire system has an open-architecture structure which allows further upgrading/integration possible.

RMSs need not be more expensive than flexible manufacturing systems or even dedicated transfer lines. Unlike other systems an RMS is designed to be installed with the exact production capacity and functionality needed, and to be upgraded (in terms of both capacity and functionality) in the future, when needed. Expanded functionality enables the production of more complex part types and the production of a variety of part types on the same system; it will be associated with adding process capabilities, auxiliary devices, more axis motions, larger tool magazines, and expensive controllers (Koren *et al*, 1999).

7. Lessons Learned

The survey results reinforce, from extensive U.S. industry experience, some key findings that have been reported in other studies (NRC 1998, Rogers and Bottaci, 1997; Ashley, 1997; Koren *et al* 1999; G.H. Lee, 1997). These are that FMS systems, due to high cost and fixed structure, cannot cost-effectively meet the needs of manufacturers to respond quickly to changing market demand. Reconfigurable manufacturing systems, designed at the outset to be upgraded in terms of functionality and capacity, may be needed in many situations. Thus, RMS is recognized as a high priority technology, but also significant research is needed before widespread use in industry. Industrial implementation of RMS is building on technologies such as modular machines (e.g., see Lamb Technicon, http://www.lambtech.com/lms_rd/title_page.htm) and open-architecture controllers. We are aware of several companies (e.g., Cummins, Uniboring, Somex) where at least partial implementation of RMS is underway.

8. Conclusions

The conclusions that can be drawn from these main results, and the many other survey results detailed in the body of the report, include:

♦ FMS addresses an important need, and continues to be part of future production system purchasing plans. However, the majority of users are not satisfied with FMS because of a variety of problems, including its lack of reconfigurability (i.e., its fixed capacity and fixed functionality).

♦ RMS is viewed as a promising technology and with its features, it has inherent capabilities for capacity adjustment, product variety and shorter changeover time.

♦ RMS, because of its modular structure and ease of integration, can complement other production systems and has the potential to address some of their shortcomings.

♦ RMS will require additional research and development in certain key technologies (e.g., training & education, modular machines, and open-architecture controls).

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