NSF Engineering Research Center for

Reconfigurable Machining Systems

Reconfigurable Machining Systems Vision with Examples

by

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RECONFIGURABLE MACHINING SYSTEMS
Vision with Examples

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Creating the new manufacturing paradigm –
– Exactly the capacity and functionality needed, exactly when needed

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Table of Contents

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Creating the new manufacturing paradigm –
– Exactly the capacity and functionality needed, exactly when needed

Manufacturing of consumer goods is the foundation of the US economy. But, to stay competitive in the 21st Century in which markets and products are expected to change in unprecedented fluctuations, manufacturing companies must possess a new type of manufacturing system whose

- production capacity is readily scalable to accommodate fluctuations in market demand,
- production functionality is rapidly adjustable to new products, and
- structure is designed to be upgradable with new process technology needed to accommodate tighter product specifications.

Current systems, even so-called flexible manufacturing systems, do not have these characteristics. Cost-effective, reconfigurable manufacturing systems, whose components are reconfigurable machines and reconfigurable controllers, as well as methodologies for their systematic design and ramp-up, are the cornerstones of this new manufacturing paradigm.

1. The Challenge

Most manufacturing industries currently use a portfolio of dedicated and flexible manufacturing systems to produce their products: **Dedicated manufacturing lines (DML)**, or transfer lines, are based on fixed automation and produce the core products or parts of the company at high-volume. Each dedicated line is typically designed to produce a single part (e.g., specific pump housing). When the volume is high, the cost per part is relatively low. **Flexible manufacturing systems (FMS)** can produce a variety of products on the same system. They consist of computer numerically controlled (CNC) machines and other programmable automation. The production capacity of FMSs is usually lower than that of dedicated lines but their initial cost is higher.

Medium and high-volume manufacturers in the U.S. are now facing new market conditions characterized by: short windows of opportunity for introduction of new products that, in turn, have shorter life time[1], and large fluctuations in product demand. To cope with the need for quick introduction of products, computer-aided design (CAD) has dramatically reduced product development times during the last decade. The manufacturing system lead-time (i.e., the time to design, build or reconfigure, and ramp-up to full-volume production) has now become the bottleneck. Reducing lead-time for manufacturing systems that produce new products provides major economic savings and is critical in responding to short windows of opportunity.

The second challenge — coping with large fluctuations in product demand — cannot be solved with dedicated lines that are not scalable to low volumes. DMLs are not scalable since **the DML is not designed for a changeable cycle time**. This challenge, however, can be theoretically solved by utilizing flexible manufacturing systems that are scalable[2]. Despite this advantage, however, our survey shows that flexible systems have not been widely adopted, and many of the manufacturers that bought FMSs are not pleased with their performance[3]. The main reasons for the low level of acceptance or satisfaction of FMS are:

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[1] Pine, 1993, *Mass-Customization,* Harvard Business School Press
[2] Koren, 1983, *Computer Control of Manufacturing Systems*, McGraw Hill, NY.
[3] Mehrabi and Ulsoy, 1997, ERC/RMS Technical Report #2.

- FMS is expensive,
- it does not utilize flexible, user-specific system software, and
- it takes a long time to ramp-up a new system (sometimes over two years).

Why is an FMS expensive? Because, unlike the DML approach, the FMS and its CNC machines are not designed around the part. First, general purpose CNCs are built, and only then does the manufacturer select the machines and perform the process-planning needed to adapt the machines and the process to the part. Since the common requirements from FMS are that it should be able to (i) produce any part (within the machine envelope), (ii) any mix of parts, and (iii) at any order (sequence) – **the typical FMS must have a parallel system structure** utilizing general-purpose CNCs, a solution which is very expensive. (By contrast, as will be shown later, the typical RMS approach calls for batch-type operation with short conversion time between batches.)

Cost-effective response to market demand requires a new manufacturing approach that enables:

- **Design of a manufacturing system around the <u>part family</u>, with the <u>customized flexibility</u> needed just for producing all parts of this part family. This approach enables one to obtain the high productivity achieved by the <u>simultaneous operation of cutting</u> tools as in DML with the high flexibility of FMS.** (Examples showing how the customized flexibility can increase productivity are in Figs. 14 & 15 below.)

- **Design of a manufacturing system for <u>adjustable resources</u> (spindles, axes). This enables adjustment of machine functionality as the product changes and adjustment of system capacity (i.e., <u>scalability</u>) as the market changes.**

As summarized in **Table 1**, a system with these features constitutes a Reconfigurable Manufacturing System (RMS). The cost-effectiveness is achieved through the customized flexibility, the option for simultaneous operating tools on a CNC-type machine, and the adjustable resources that enable scalability and adaptability to new products. Resources may be adjusted at the system level (e.g., adding machines) and at the component level (machine hardware and control software). The main components of RMSs are CNC machines and Reconfigurable Machine Tools (RMTs) – a new type of machine that has a changeable structure enabling the adjustment of its resources (e.g., adding a second spindle unit) according to the need.

Table 1. RMS combines features of dedicated and flexible systems

|	Dedicated	RMS/RMT	FMS/CNC
System Design Objective	The Part	The Part Family	The Machine
Resources	Fixed	Adjustable	Fixed
Flexibility	No	Customized	General
System Scalability	No	Yes	Yes
Simultaneous Operating Tools	Yes	Yes	No

The definition of a reconfigurable manufacturing system is, therefore, as follows:
A Reconfigurable Manufacturing System (RMS) is one designed at the outset around a part family and for rapid adjustment of its production capacity and functionality by changes of its whole structure as well as its hardware and software components.

Unlike FMS and CNC which solve a forward problem, the RMS poses an **inverse problem**: Given a part family with stochastic time-varying demand and mix, determine the optimal machining system for producing these parts [P. K.]. If the demand is always fixed – RMS is not needed and DML should be used. Obviously, RMS requires a definition for a part family. In the context of RMS, **a part family may be defined** as all parts that have similar geometric features and shapes, the same level of tolerances, require the same processes, and have the same range of cost[4]. These new reconfigurable manufacturing systems must be able to rapidly convert to the production of new products of the same product family, and be designed to produce them in unpredictable quantities. Such systems do not exist today, nor their design and reconfiguration methodologies.

2. Example

The design process of a RMS will be explained through an example of the part family depicted in **Fig.1**. A manufacturing system that can produce parts A and B is needed.
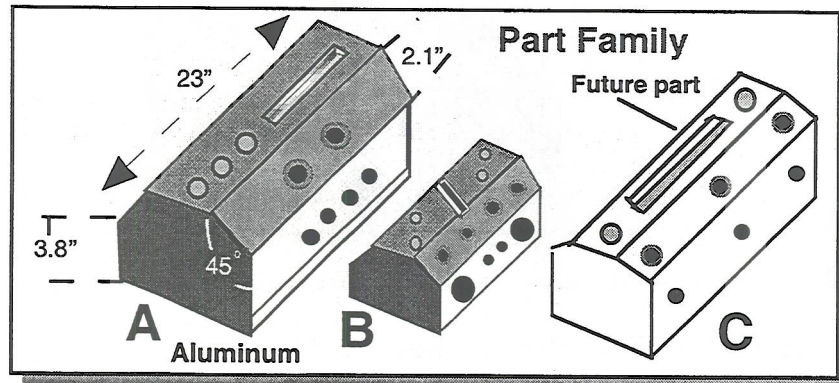
Figure 1. Example of a part family. A manufacturing system that produces parts A and B is needed. Part C is a future part, unknown at the system design stage.

At the design stage the market forecast shows that 300 parts/day of part A and 200 parts/day of B will be needed. Later, as the market grows (see **Fig. 2**) the system capacity will have to be scaled up to produce 600 of A and 300 of B, for a total of 900 parts/day.
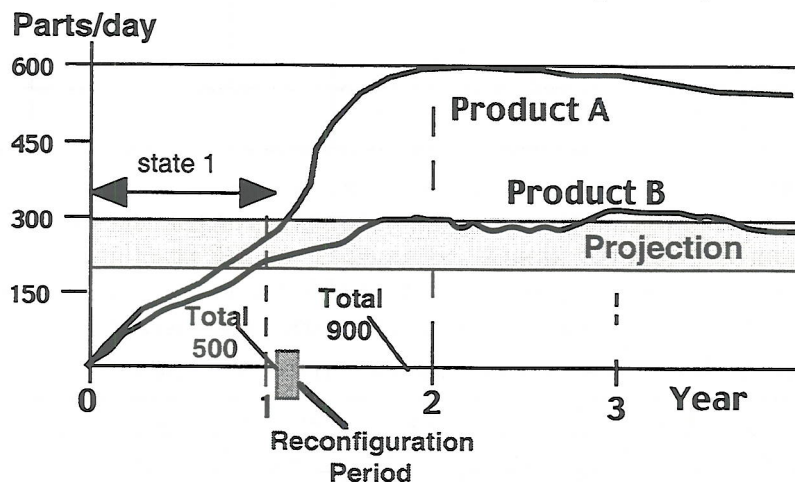
Figure 2. The projection and real market behavior for parts A and B. The original system capacity is 500 parts per day. At year 2 the capacity has to be increased to 900 part/day.

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[4] S. Sanderson and M. Uzumeri in *Managing Product Families*, Irwin, 1997, define product families in the contex of product design and strategic management.

2.1 DML Design.   The design of a <u>conventional</u> dedicated system requires the design of two lines: one for part A and the other for part B. Let us elaborate on the design of a DML for part A. As shown in **Fig. 3**, the part has seven basic features (a basic feature is machined with the same cutting tool in one operation) and therefore the simplest solution requires seven stations, with one for each operation. The time and power needed for each operation is shown in **Table 2.**   The power requirement in Table 2 affects the cost of the machinery and is also needed for the grouping process in RMS design (that will be presented later).
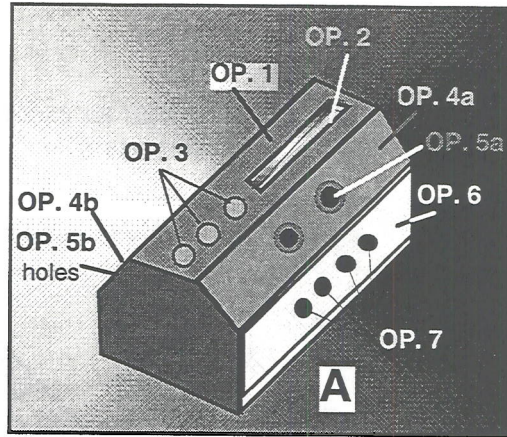

Fig. 3. Part A has seven basic features requiring seven operations

Table 2. The time and power needed for each operation on Part A.

Surface	Top surface	Top slot	Top holes	Left angled surface	Left angled holes	Right angled surface	Right angled holes	Side surface	Side holes
Operation	Op. 1	Op. 2	Op. 3	Op. 4a	Op. 5a	Op. 4b	Op. 5b	Op. 6	Op. 7
Time in seconds	23	16	14 14 14	20	9 9	20	9 9	25	15 15 15 15
Power [HP/feature]	10	8	1	7	1	7	1	15	1

The multiple holes are produced simultaneously by gang drilling (i. e., by a drilling head). The longest operation is Op.6 that requires 25 seconds. The transfer time between stations is 5 seconds. Therefore, the cycle time is 30 seconds, or 120 parts/hour. Assuming an ideal reliability of 100%, the line can produce up to **1920 parts in a 2-shift operation.** The lines have lots of idle capacity and can respond to market increase, but not to new product.

Table 3. The time and cost per station in the dedicated machining line

Operation	Op. 1	Op. 2	Op. 3	Op. 4•	Op. 5•	Op. 6	Op. 7
Time [sec]	23	16	14	20	9	25	15
No of axes	2	2	1	2	4	2	2
Power [HP]	10	8	3	14	4	15	4
Tools	one	one	cartridge	Two sides	Two cartridges	one	cartridge
Cost/station [$K]	200	200	200	260	320	240	280
Total cost/Line	$1.7 million						

The cost of the stations is shown in **Table 3**. The total cost of the line is $1.7 million. **The cost of two lines, for parts A and B, is $3.4 million.**

2.2 FMS Design. The FMS consists of 5-axis CNC machines, rated at the maximum power needed (15 HP), each with a tool changer that contains all the 24 tools needed for parts A, B, and C. The total cutting time of part A with a **single tool** is 242 seconds (see **Table 4** "CNC Time"). The tool changing time is 45 seconds (9 changes at 5 seconds each), and the total positioning time is 95 seconds (2 seconds between holes and 4 seconds for axis rotation). The total cycle time is 382 seconds, which yields a rate of 9.4 parts per hour. Assuming again a reliability of 100%, **each machine can produce 150 parts/day.** In order to produce the 500 parts/day needed in the first state, four machines are needed in a 2-shift operation (FMS 1). **Six machines are required for the second state of a rate of 900 parts/day (FMS 2).** (For comparison, each line of the DML can produce 1920 parts.)

Table 4. Comparison of production rate of DML and CNC.

Operation	T i m e [sec]									Cut	Tool Change	Tran sfer Posit	Cycle time	Parts per Hour	Total # Parts (2 shifts)
	1	2	3	4a	5a	4b	5b	6	7						
DML	23	16	14	20	9	20	9	25	15	25	0	5	30	120	1920
CNC	23	16	42	20	18	20	18	25	60	242	45	95	382	9.4	150 per machine

Each CNC machine in this type of parallel FMS is relatively expensive since it must meet three requirements: (i) five axes of motion, (ii) highest needed power, and (iii) a large tool changer to produce all the parts of the part family. [We recognize that there are cases in which a 4-axis machine is adequate, but we analyze the general case.] At a cost of $750,000 per machine (see Table 6), the **system cost at the first state (FMS 1) is $3 million**, which is less expensive than the dedicated system. However, in the second state **after reconfiguration the FMS cost is $4.5 million**, which is more expensive than the DML solution. Note that with the FMS there is no access capacity, and we must pay more if market demand goes up. However, the same system can produce Part C, when needed.

2.3 Discussion on the RMS Design Approach. The FMS traditional design approach is that off-the-shelf CNC machines are offered, and the part manufacturer selects a machine that fits the geometric envelope of the part. Subsequently, the manufacturer fits the part processing to the machine capability through process plans. If the part has surfaces that do not coincide with the main vertical or horizontal plans of typical 3-axis (X, Y, Z) machines, rotary and tilt axes must be added to the machine. The addition of these two axes-of-motion increases the cost and reduces the machine reliability.

If the design process had been changed, and the machine would be designed around the part, cost could be reduced and reliability improved. However, to be economical, the machine design should be around a part family, rather than a single part. Furthermore, if an increased productivity is needed, the structure of a traditional CNC is not designed for augmenting machining resources (e.g., adding a spindle or an axis), and a new type of CNC machine that has a structure that is designed for a change (i.e., for reconfiguration) is needed.

Our hypothesis is that cost-effective response to market demand requires a new manufacturing approach that enables:

- **Design of the <u>machine tools</u> around the part family, with the customized flexibility needed just for producing all parts of this part family** (rather than the general flexibility offered on traditional CNCs).
- **Design of the <u>system</u> for a changeable cycle time** (i.e., reciprocal of productivity) – it enables system scalability, a feature needed in systems designed **for medium to high-volume production.**
- **Design of the <u>machine</u> (i.e., a reconfigurable machine tool, or RMT) for adjustable resources (spindles, axes, and cutting angles).** This feature enables adjusting machine functionality as the product changes and adjusting machine productivity as the market changes.

This approach must be built upon a systematic transformation of part family requirements into machine specifications, as explained below. Starting with the part family, the designer groups the machining operations needed on the part family according to the following hierarchy:

1. **Operations are performed on different surfaces but require coordination, such as tolerances between intersecting holes located on different surfaces.**

2. **Operations that are performed on the same surface of the main part surfaces. Examples include tolerance-based clustering on the same surface, or parallel holes that can be drilled simultaneously by tools driven by one set of axes at fixed orientation (gang drilling)**

3. **Pattern of similar operations across the part family**

The design for cycle time is performed in parallel to step # 3.

The first requirement means, for example, that the two surfaces from which the intersecting holes are drilled must be located on the same machine in order to achieve a precise intersection point. The second step calls for the **design of a machine that exactly fits the motions on the main part surfaces, namely, design around the part. This is the most revolutionary concept in the RMS design process.** With current practice, when a part requires machining of surfaces that are not parallel to the main plans (X-Y or X-Z), additional rotary and tilt axes are needed either on the machine or on the fixture, which, in turn, increases the cost of the system. **In a paradigm in which the machine is built from a library of primitive motion-blocks to fit the part surfaces, process planning is performed simultaneously with the design of the machine.** This is a revolutionary change compared with traditional process planning, a change that will enable the use of simple fixtures that do not have axes-of-motion. The first requirement, however, is stronger than the concept of building the machine around the part. Note that operations on the same part surface do not have to be machined on the same machine. Cycle time comes into play here. In the last step the change between our approach and the traditional one is that we deal with the features across a part family, whereas traditional methods deal with a single part.

2.4 Design of RMS 1. In our particular example, coordinated operations on different surfaces do not exist, and we start the design in step 2. Part A has three main surfaces. Therefore, the design process may start with a system that consists of three machines that are arranged in series (a line). Each machine is suited to perform operations on one main surface:

   I –   a vertical milling machine (VMM) for operations 1 to 3,

   II –   a special arch-type reconfigurable machine tool (RMT) that is built to fit the angled surface for operations 4a, 5a, 4b, and 5b, as shown in **Fig.** 4 (left), and

   III –   a horizontal milling machine (HMM) for performing operations 6 and 7.

Note that the arch-type machine in Fig. 4 (left) is only an example of a 3-axis reconfigurable machine with axes that do not coincide with the usual Cartesian coordinate system. There are several other possible designs, such as a machine that has a triangular shape with an angle that fits the part angled surface. Furthermore, RMTs may be also horizontal and vertical machines designed with the option of adding and subtracting axes of motions and spindles. The main issue, however, is how to develop a **RMT design methodology that will provide in a systematic way a rigid, cost-effective structure that will enable quick reconfiguration across the parts of a particular part family.** Note that RMTs are needed also for parts that do not have angular surfaces. The main requirements of RMTs are (i) the quick conversion of the machine to produce different parts of the same family, and (ii) the quick reconfiguration of the machine to increase productivity as market grows or to change functionality as product changes. (Note that we distinguish between conversion period, which is measured in minutes, and reconfiguration period which is measured in days).
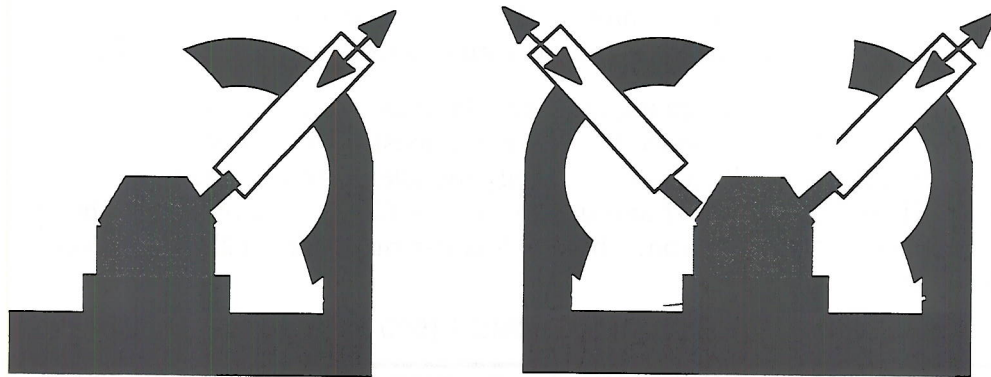

Fig. 4. Reconfigurable machine tool. Left – first state (II), right – after reconfiguration (II^).

Next, we have to look at the cycle time. **In a typical RMS environment the operation is performed in batches:** Part A is first produced, then the system is stopped for a switchover, or a conversion, a period in which hardware and software are converted to fit Part B. The operation is then resumed and Part B is produced. The next day, the operation starts

Table 5. Comparison of production rate of four systems: DML, FMS, and two RMSs

Operation	Time [sec]									Cut	Tool Change	Transfer Posit	Cycle time	Parts per Hour	Total # Parts
	1	2	3	4a	5a	4b	5b	6	7						
DML	23	16	14	20	9	20	9	25	15	25	0	5	30	120	1920
FMS	23	16	42	20	18	20	18	25	60	242	45	95	382	9.4	900
RMS 1: Machining time			81	I		61		III	85						
Tool Change			15		II	15			10						
Positioning time			10			12			10						
TOTAL TIME			106			88			105	106		5	111	32.4	500
RMS 2: Mach. time		39	42			29			40						
Tool Change	I	10	IV 0	II^		10		III	10						
Positioning time		4	6			6			4						
TOTAL TIME		53	48			45			54	54		6	60	60	925

with the production of Part B, and then part A. To guarantee efficiency, **the conversion time should be small (e.g., between 15 to 45 minutes)**.

This batch-type operation mode that requires conversion time between batches brings up the question: what happens if there is a large number of different parts with small batches that should be produced on the same system? Where is the economic breakeven point between this type of operation and operation with a conventional flexible system in which parts may be produced at any arbitrary order and mix? (**ERC/RMS Project 1.1 should deal with this issue.**)

In this example we assume a 30-minute conversion time (one conversion between A & B). At the first system state (called RMS 1) the required capacity is 500 parts/day (300 of A and 200 of B). The target cycle time (two shifts) for **RMS 1** is

$$15.5 \times 3600/500 = 111.6 \text{ seconds}$$

The cycle time for each of the three machines in RMS 1 is shown in **Table 5**. The longest operation (with a single tool) is 106 seconds. Adding to it the 5 seconds transfer time results in a cycle time of 111 seconds, similar to the target cycle time. If this cycle time had been longer, we could add machines or introduce a simultaneous operation of tools.

Each machine in the RMS design requires only three tools, since tools may be changed during conversion time. The CNC machine, however, must contain a set of 24 tools needed to machine all operations on all parts of the family (parallel system). The cost of each of the three machines (I, II, and III) in RMS1 and the cost of the CNC are shown in **Table 6**. The total cost of the system is $1.53 million, which is less expensive than either the FMS ($3M) or the DML ($3.4M).

Table 6. Machine cost for RMS 1 (500 parts/day) and FMS 1

Machine	I - VMM	II - RMT	III - HMM	CNC
Axes	3	4	3	5
Tool Changer	3 tools	3 tools	3 tools	24 tools
Power [HP]	10	7	15	15
Features		Rotary table		
Machine Cost [$K]	320	390	370	500
Tool Changer [$K]	50	50	50	150
Material Handling	100	100	100	100
Total Unit Cost [$K]	470	540	520	750
System Cost	RMS 1 = $1.53 M			FMS 1 = $3 M

2.5 Reconfiguration – Design of RMS 2. In the second state the RMS must be reconfigured to produce 900 parts/day (see Fig. 2). The cycle time for this new configuration – RMS 2 – is calculated as follows:

$$15.5 \times 3600/900 = 62 \text{ seconds}$$

As shown in Table 4 and in **Fig. 5**, this smaller cycle time is achieved by a system reconfiguration that includes **resource adjustments of three different types**:

- Adding one additional vertical milling machine (machine IV) to drill the three holes with a single tool. This machine has a low power (1 HP) and no tool changer.

- Adding a second spindle unit to the existing RMT (see Fig. 4, right) to allow machining of the two angled surfaces simultaneously. This reconfiguration also includes removing the rotary table from the machine since it's not needed now, and may be utilized elsewhere.

- Adding a special cartridge with four drill bits as a "tool" (i.e., performing *gang drilling*) in the tool changer of the existing HMM to enable simultaneous drilling of the four holes on the side surface in order to reduce the machining time on this station.
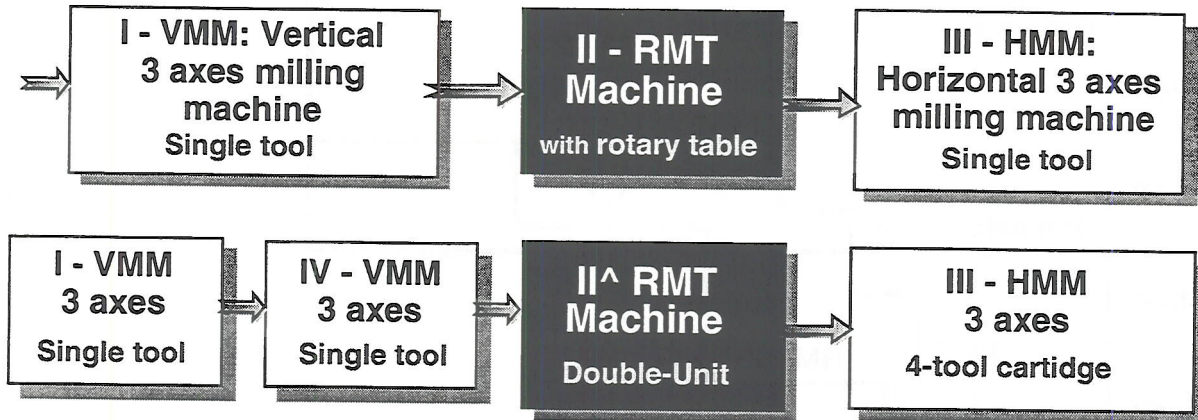
I - VMM: Vertical 3 axes milling machine **Single tool**	→	**II - RMT Machine** with **rotary table**	→	III - HMM: Horizontal 3 axes milling machine **Single tool**

I - VMM 3 axes **Single tool**	→	IV - VMM 3 axes **Single tool**	→	**II^ RMT Machine** **Double-Unit**	→	III - HMM 3 axes **4-tool cartridge**

Figure 5. The two states of the reconfigurable system: RMS 1 (top) and RMS 2 (bottom).

As shown in **Table 7**, the cost of the equipment after reconfiguration is $2.2 million. (There is a need for a ramp-up time after reconfiguration, and, although for simplicity it is not considered here, the opportunity-loss cost must be also accounted for as well. **A rapid ramp-up time reduces the opportunity-loss cost and becomes critical for successful reconfiguration.**) However, the designer may choose to add the more expensive machine of type I (see Table 6) rather than the smaller machine of type IV, a decision which is economically justified if future system expansion is considered (see scalability charts below). This brings the total **cost of RMS 2 to $2.3 million.**

Table 7. Machine and system cost for 900 parts/day (after reconfiguration)

Machine	IV - VMM	I - VMM	II^ - RMT	III - HMM	CNC
Axes	3 axes	3 axes	5 axes	3 axes	5 axes
Tool Changer	No	3 tools	3 tools	3 tools	24 tools
Power [HP]	1	10	14	15	15
Features			Double spindle	Tool cartridge	
Machine Cost [$K]	270	320	600	390	500
Tool Changer [$K]	0	50	50	120	150
Material Handling	100	100	100	100	100
Total Unit Cost [$K]	370	470	750	610	750
System Cost [$K]	RMS = $2.2M				FMS 2 = $4.5M

Scalability charts for the three systems are shown in **Fig. 6**. For volumes between 900 and 1400 parts per day, we recommend building an additional RMS line, namely [RMS2 + RMS1], for a total cost of $2.3M + $1.53M = $3.83M. This cost, although higher than the $3.4M needed for two dedicated lines, is still economically justified since the RMS provides the option of reutilizing the equipment when the product is phasing out and smaller volumes are needed. (Considerations like that must be accounted for in the life-cycle economic model developed by Project 1.1.)
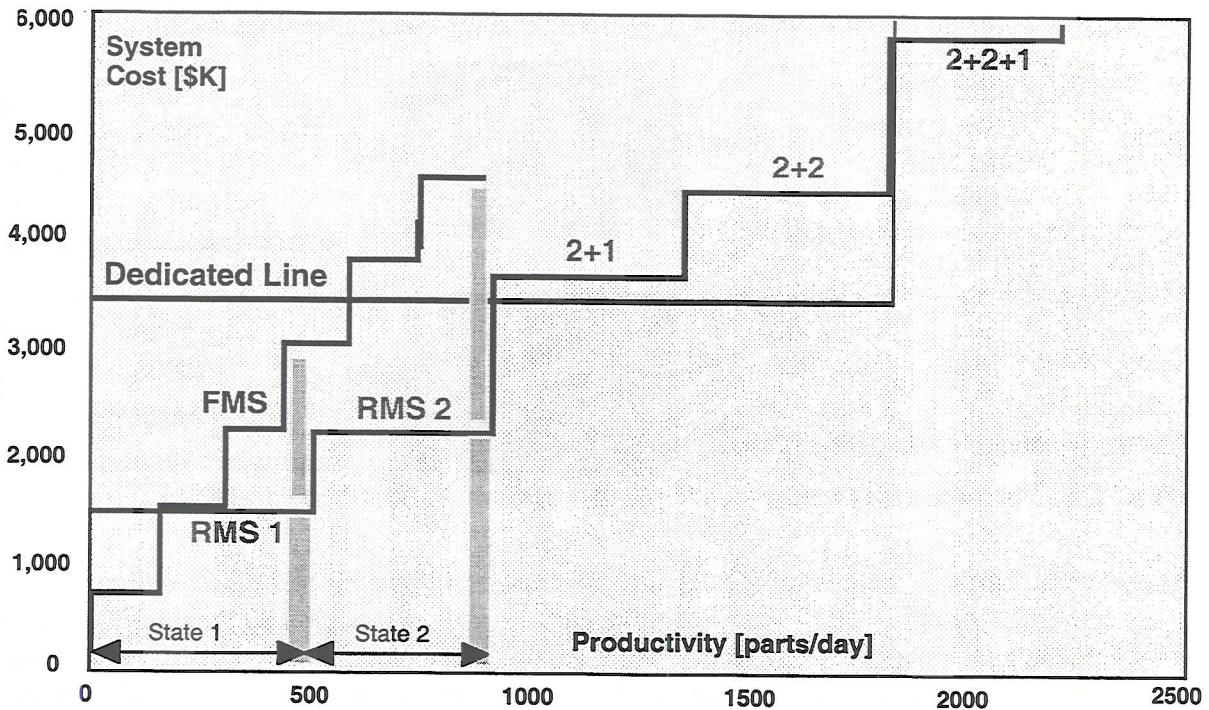
Figure 6. Scalability charts for RMS and FMS for the example (DML capacity for comparison)

For volumes above 1400 per day, RMS 1 can be upgraded to RMS 2, providing the solution of [RMS2 + RMS 2] for a cost of $4.6M and volumes of up to 1800 parts per day. Is this solution justified economically? We cannot answer this question now; it requires more research.

In summary, for a mix of parts A and B, the conclusions for this example are:

♦ FMS is the preferred solution for volumes of less than 300 parts/day.

♦ DML is the preferred solution for volumes of 1400 or more and stable markets.

♦ RMS is the preferred solution for volumes between 300 and 1400 per day, and also for larger volumes when operating in an environment of unpredictable markets.

3. Adding a Future Part

With the RMS approach, when a future part (Part C in Fig. 1) is introduced, in addition to loading a new part program the machines must be also reconfigured to fit the new part geometry. The point is that the system was designed at the outset to accommodate additional parts of the family, and therefore the reconfiguration period should be small. For this reason, the RMT in Fig. 4 has the arch-type design. The arch is a rotary slide with a readable scale along which the spindle unit can be moved and adjusted to fit the desired angled-surface of the part. This degree-of-freedom (DOF) is a "reconfigurable DOF" and it allows easy reconfiguration of the machine. If a servomotor is added to this axis, it may be also utilized

during conversion (we assume 15 to 30 minutes conversion time between batches). **Figure 7** shows the various axes of motion of the double-unit RMT. We can see how the machine can change its shape and be reconfigured to fit the part. Note that even if the arch axis is motorized, it is not a regular axis since it is not designed to work continuously. It may be moved a short distance once or twice a day during conversion periods, and therefore it is much cheaper than a regular axis of motion that is designed to work continuously.
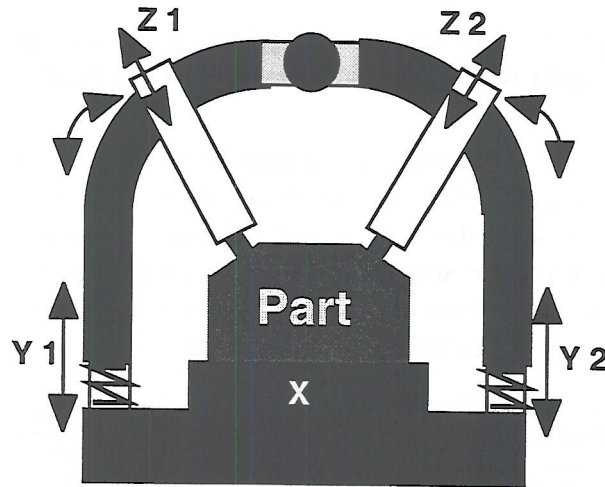
Figure 7. An example of a RMT and its axes of motion.

The challenge in designing RMTs is to develop a machine design methodology that based on tool path requirements creates the appropriate RMT from building blocks of basic axial motions. Given the part surface and tool path and orientations, this design methodology should suggest the kinematics of a new RMT and analyze its dynamic stiffness. **The creation of RMT design methodology based on a library of building blocks is the task of the team in Project 4.1.** The input to 4.1 is the tool path and orientation from the process planning performed in Project 5.4. **Predicting machine deformations caused by cutting forces and changing machine temperature in parallel processing environment (i. e., multiple spindles) is the task of Project 5.1.** To create a rigid machine, input from Project 5.1 must be given to Project 4.1.
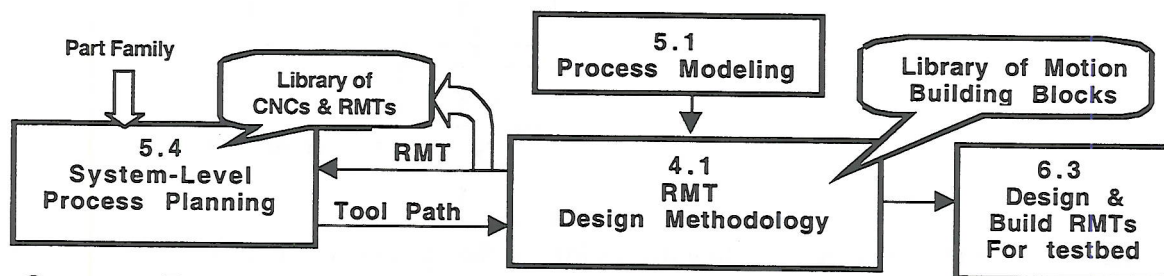
4. System Design

In the above example we introduced important concepts in Design for Reconfiguration. However, many steps in the design process of this example are experience-based. **The systematic design of reconfigurable systems requires a concrete methodology,** supported by software tools, that relates the product features and cycle time to modules of processing units and yields a system layout where operations are distributed across the machines in a balanced manner. Furthermore, together with the system design the manufacturer must be furnished with scalability and reconfiguration plans for different market scenarios. **The development of this methodology with the supporting software tools is the task of Project 5.4.**

The team of Project 5.4 must work closely with the team of Project 4.1 in which a methodology to design reconfigurable processing units that fit the desired part family is being developed.

A most critical decision in this process is the selection of the system configuration. The arrangement of the processing-units in series, in parallel, or in different hybrid configurations has a profound effect on factors such as

(i)   product <u>quality</u> variations,
(ii)   overall system productivity (depends on <u>reliability</u> and <u>part mix</u>),
(iii) the ease of <u>scalability</u> (adding incremental production capacity), and
(iv)   investment <u>cost</u>.

In the example above we designed the systems with either serial or parallel structure. However, as shown in **Fig. 8**, there are additional eight combinations that are possible with four machines. We should develop a methodology to analyze all possible, feasible configurations and a criterion for selecting a system. Selecting the optimal solution from the large number of possible alternatives (more than 2^{n-1} for n machines) requires the development of configuration rules – such rules that do not exist today.
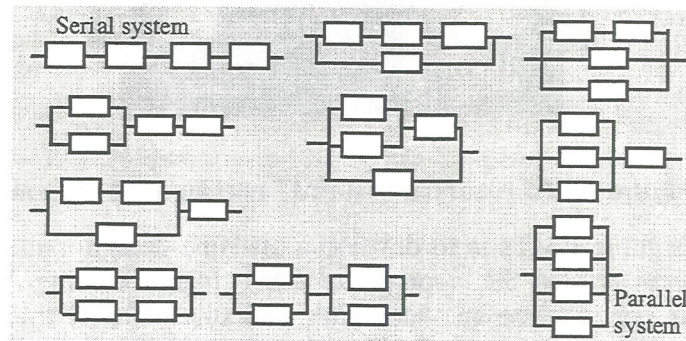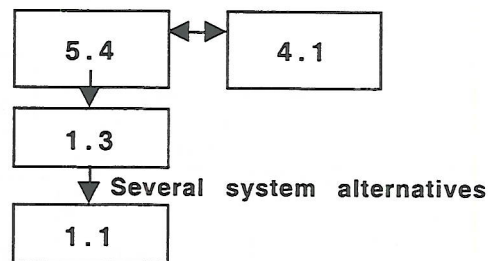

Figure 8. Ten system configurations are possible with four machines.

The development of configuration rules combined with analysis methodology and the supporting software tools is the task of Project 1.3. The team of Project 1.3 must work closely with the team of Project 5.4 to enable the achieving of a comprehensive methodology.

Finally, life-cycle economic modeling that estimates the system cost during its entire life-time, and accounts for future product changes and uncertainty in market conditions, must be used to select among the feasible manufacturing system alternatives. **The development of life-cycle economic models and the consequent analysis methodology and the supporting software tools is the task of Project 1.1.**

The successful completion of these projects will help us to leapfrog into the RMS paradigm. In the RMS paradigm CAD tools will be available for the design of production systems, and not only for the products that they produce.

5. Reconfigurable Control

In many cases when the machine is reconfigured (or even when converted) the controller must be reconfigured as well. For example, simultaneously with the mechanical change (i. e., machine reconfiguration) of the two states in Fig. 4, the control must be changed as well. The corresponding two states of the reconfigurable controller are shown in **Figs. 9a** and **9b**. The control reconfiguration in this example includes several types of reconfiguration:

(v)   Integrating additional servo-controllers and tool breakage detector modules into an existing controller (this is a control **hardware** reconfiguration, but with a different controller this may be a software reconfiguration).

(vi)   Changing either interpolation parameters or the algorithm of the Axis Group Coordinator (the interpolator depends on the angle between the Y-axis and the Z-axis).

(vii)   Changing the algorithm of the compensator for machine temperature related error – it depends on the machine configuration.

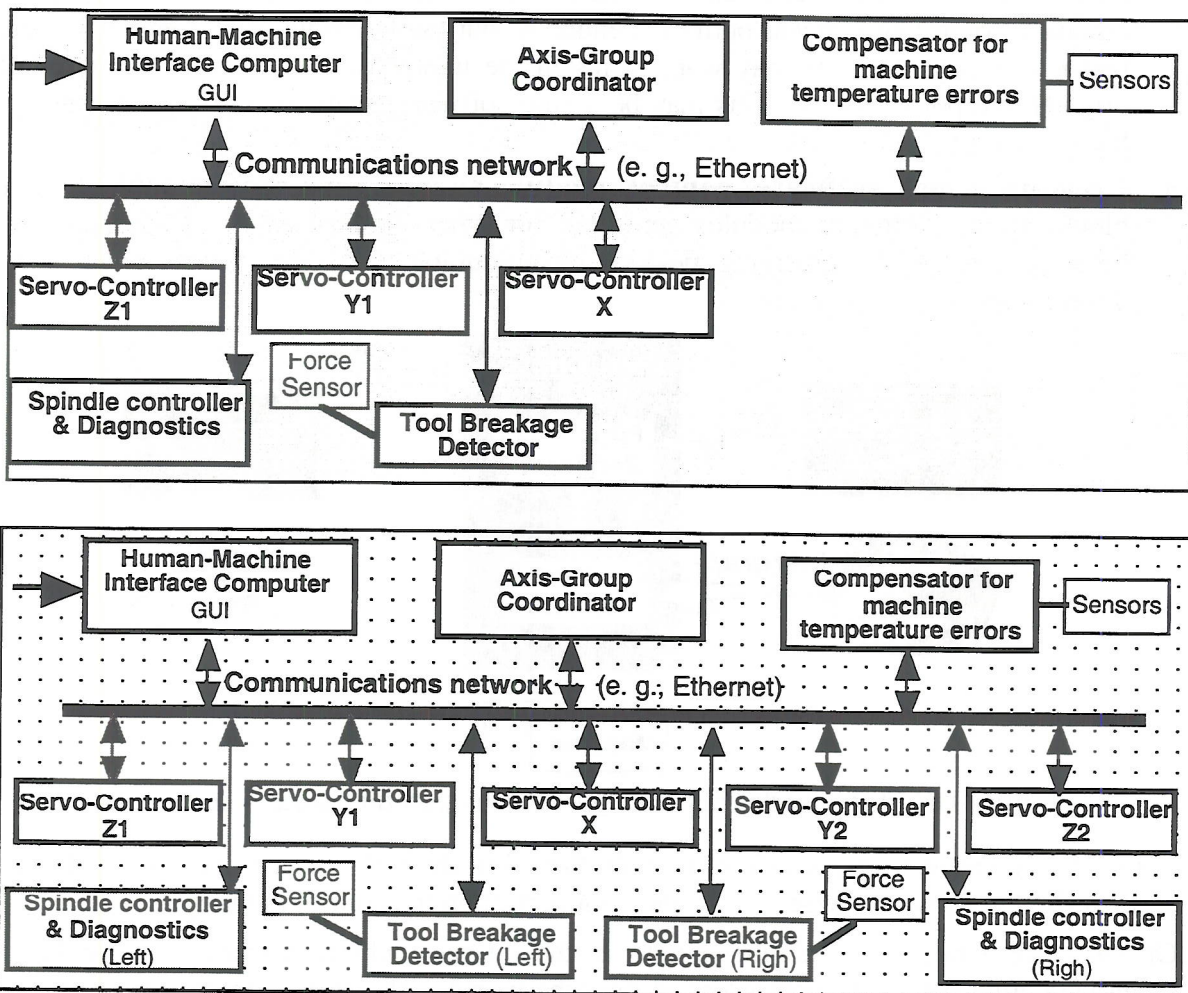(viii) Changing constraints and specifications in the servo-controllers – they depend on the machine configuration.

Figure 9. The control system of the RMT in Figure 7 (a) before (top) and (b) after reconfiguration.

The control reconfiguration may include hardware (e.g., the first item above) or software reconfiguration (the last three above). It is preferable that the software reconfiguration should

be done remotely through a Human-Machine Interface (HMI). Following the hardware reconfiguration (if needed), reconfigurable controllers requires therefore two basic modes of operation:

- Configuration, or set-up mode, in which the control parameters and internal structure of all control modules is set by software from a remote computer (non-real-time mode), and

- Operation mode, which is the regular real-time execution mode for the controller.

5.1 Open-Architecture and Reconfigurable Controllers. The technology of open architecture control systems (OACS) is needed for the implementation of reconfigurable controllers. There are three main aspects, or modes, of OACS (see Fig. 10):

- **Adding new control or measurement modules** into existing control systems. For example, adding a sensor to an existing CNC controller and integrating the sensor output with the original controller. This mode involves both hardware and software aspects, and it generates the highest benefits of OACS technology.

- **Swapping modules**, that can be a hardware or software module. For example, if a complete control system was built by Vendor A, but the interpolator of Vendor B results in better accuracy, the user may want to install the interpolator of Vendor B instead of the original interpolator of A. This may be a pure software swap, or a change that replaces a hardware unit.

- **Creating a new software control module** by integrating existing software building blocks (i. e., software modules generated for other applications). This mode, which belongs to a broader emerging field of reconfigurable software, saves control software development cost.
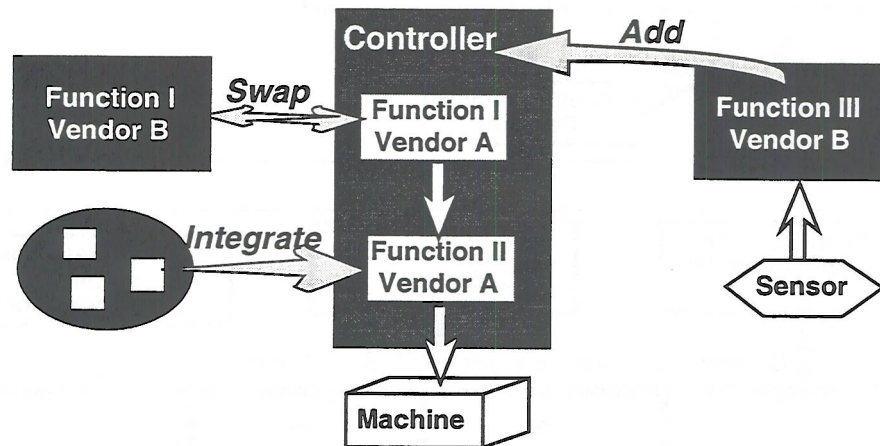

Figure 10. Three modes of reconfiguration in open-architecture controllers.

Since 1986 there were major efforts to build OACS in the US, Europe and Japan. However, none of these efforts has caused any significant impact on the control industry.

On the other hand, we watch the growth of the Internet, which is essentially one big open system that links individual computers all over the world. The computers that are connected to the Internet run the communication standard TCP/IP (Transmission Control Protocol/Internet Protocol). This universal standard allows different types of computers to communicate with each other, regardless of their make, model, or operating system. We believe that if a similar solution is adopted in factory and machine control, we could accomplish the first two aspects of OACS. However, there is one big difference: The Internet is not a real-time system.

We envision a reconfiguration environment in which the various modules do not communicate directly, but through a communications network or a bus (e.g., Ethernet, Sercos, Canbus), similar to a distributed control environment. This requires high-bandwidth communications networks, which are rapidly becoming a reality. The underlying hardware network (Ethernet, Sercos) is completely invisible to the modules. The modules "see" the software layer that implements a protocol layer on top of it. This software layer must be designed so that both configuration and real-time communications can be accomplished transparently. If we decide to use the Ethernet in our projects, an important research topic is how to make the Ethernet a real-time system? Eventually, we want to develop a real-time "factory-net" that will be easy to use as the internet has been.

The network delays in information transfer and in executing cross-axial algorithms, such as the Cross-Coupling Controller[5,6], must be considered. Furthermore, if a certain module requires priority (e. g., a tool breakage detection that must stop the axial servo-motors immediately), it cannot get it on the Ethernet, and alternative methods of establishing priorities must be found. One method is the utilization of hierarchical Ethernet network. The ease of adding control modules to the system and the issue of precision deterioration caused by the communications network are important research issues[7]. In other words, we are dealing with open-architecture control environment in which all the communications among the various modules are done through messages. Research issues include:

- What are the tradeoffs between machining speed and precision and the level of openness and delays achieved with the communications network?
- How does one set real-time priorities on the Ethernet?
- What is the set of input and output parameters (or specifications) that each type of modules should be able to receive and transmit?
- How does one guarantee real-time hard deadlines in a reconfigurable environment?

5.2 Modular, Reconfigurable Controllers.

The open-architecture research should be coordinated with the OMAC group, and controller APIs (Application Programming Interfaces) developed by OMAC should be utilized and evaluated. In parallel with this activity we should develop

- A comprehensive control simulator with a reconfigurable, modular structure that can detect dimensional errors and cycle time in reconfigurable machines and reconfigurable systems.
- A control method to generate the control code for multi-spindle reconfigurable machines, even in cases where the part is not symmetric and each spindle operates independently, but in coordination with the other spindle.
- A control method to generate the control code for reconfigurable systems, where spindles can be added and subtracted and parts may be routed in several ways.

These control methods (which will be a combination of discrete event control and g-code) and the reconfigurable simulator will open a new avenue in machine control research.

This research work must be accomplished by a coordinated effort by the team of Project 2.1 (computer science experts developing open-architecture principles)
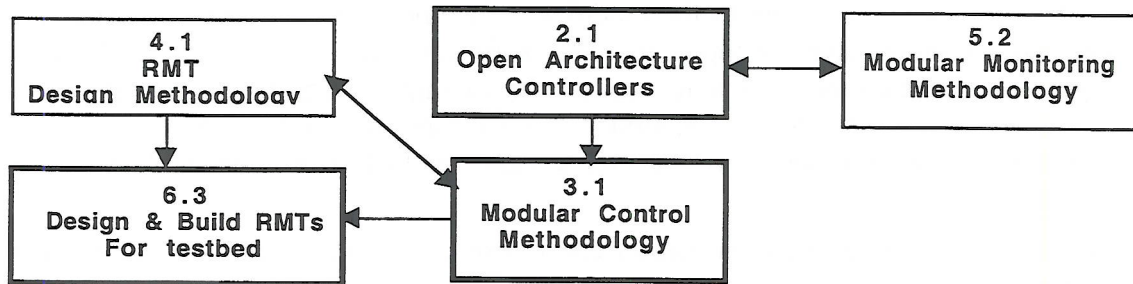
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[5] Koren, ASME, 1980
[6] Koren & Lo, CIRP,1991
[7] Koren, Pasek, Ulsoy & Benchetrit, CIRP, 1996

and the team of Project 3.1 (control experts developing modular control systems). Close interaction is needed between Projects 2.1 & 3.1 and Projects 4.1, and 5.2 (process monitoring, temperature compensation and tool breakage algorithms).

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┌─────────────────┐      ┌─────────────────┐      ┌─────────────────┐
│      4.1        │      │      2.1        │      │      5.2        │
│      RMT        │      │Open Architecture│◄────►│Modular Monitoring│
│Design Methodology│     │   Controllers   │      │   Methodology   │
└─────────────────┘      └─────────────────┘      └─────────────────┘
        │                        │
        ▼                        ▼
┌─────────────────┐      ┌─────────────────┐
│      6.3        │      │      3.1        │
│Design & Build RMTs│◄───│Modular Control  │
│   For testbed   │      │   Methodology   │
└─────────────────┘      └─────────────────┘
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6. Requirements and Enabling Technologies for Reconfiguration

The common denominator for the existing dedicated and flexible systems is that they use **fixed hardware and fixed software**. For example, only part programs can be changed on CNC machines, but not the architecture of the software nor the control algorithms. Therefore, these systems are static systems and are not reconfigurable.

During the last few years two technologies that are necessary enablers for reconfiguration have emerged: (i) modular, open-architecture controls that aim at allowing reconfiguration of the controller, and (ii) modular machine tools that aim at offering the customer more machine options. These emerging technologies show a trend toward the design of systems with **reconfigurable software** and **reconfigurable hardware**, as depicted in **Figure 11.**

The reconfigurable hardware and software are necessary but insufficient conditions for a true RMS. The core of the RMS paradigm is a systematic approach to reconfiguration based on <u>system design</u> combined with the simultaneous design of open-architecture <u>reconfigurable controllers</u> with <u>reconfigurable machines</u> that can be designed by synthesis of motion-modules. The RMS paradigm will also create a new generation of reconfigurable machines that allow an effective reconfiguration. Both the reconfigurable systems and the reconfigurable machines must be designed at the outset to be reconfigurable, and must be created by using basic hardware and software modules that can be integrated quickly and reliably.

The main requirements of RMTs are

- the machine is designed around a part family with quick conversion of the machine to produce different parts of the family,

- quick reconfiguration of the machine to increase productivity as market grows or to change functionality as product changes or process technology changes

- integration of machine modules with control modules, such that the control reconfiguration can be executed simultaneously with the machine reconfiguration

- modular structure with motion modules designed for integration, where the effect of the adapters (joints) between modules on machine stiffness is known and the estimation of the machine stiffness is possible when the stiffness of the individual modules is given.

The reconfigurable machine tool and the reconfigurable controller as well as their design methodologies are critical RMS enabling technologies.

	Fixed Hardware	Reconfigurable Hardware
No Software	Manual Machines, Dedicated Manufacturing Lines	
Fixed Software	CNC, Robot, FMS	Modular CNC Machines
Reconfigurable Software	Modular Open-Architecture Controller	RMT ↓
System configuration rules & economics	⟹	R M S

Figure 11. Classes of manufacturing systems

A key characteristic of RMT machines is that by being modular they might be designed with smaller number of active axes-of-motion that provides all the flexibility needed to produce a part family. We call this characteristic **customized flexibility.** This characteristic also allows the use of several tools that cut simultaneously, thereby increasing the productivity to the level achieved by DMLs. Note that this concept combines active degrees-of-freedom (driven by motors) with reconfigurable degrees-of-freedom (manually reconfigured) to achieve the customized flexibility.
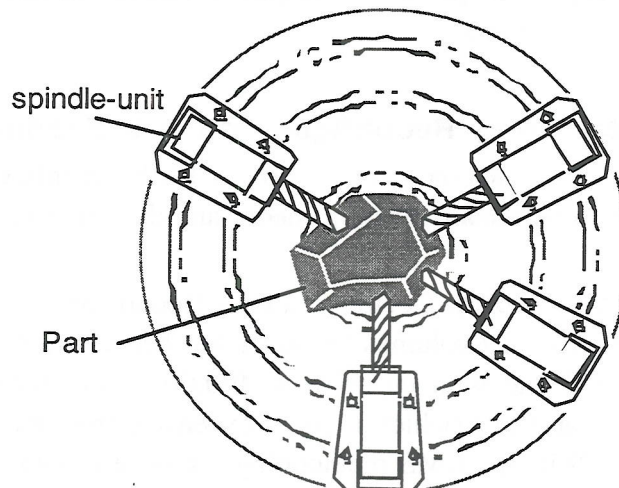

Figure 12. Example of a reconfigurable machine tool (concept by Y.K.; artist: Rodney Hill, 1994). Single-axis spindle modules are basic building blocks that can be rapidly installed around the part at different angles. The part moves in an axis vertical to the shown plane.

For example, in the conceptual reconfigurable machine depicted in **Fig. 12,** several cutting tools attached to four spindles operate simultaneously on the part. The machine is designed for

a family of parts that require drilling at different angles around the part. The reconfiguration from part A to part B requires a change of the number of spindles and their location on the machines. This machine does not have the general flexibility of a multi-axis CNC machine, but has only a "customized flexibility" that changes with the configuration.

The challenge in designing reconfigurable machines is to extract the key geometric features of several parts from a part family and to design a machine that can produce all these parts. The concept of design for a **part family** is the essence of designing a reconfigurable machine and reconfigurable system. If a capability to machine any arbitrary part is required, then FMS with conventional CNCs rather than RMS is the desired solution.

The reconfigurable system should allow flexibility not only in producing a family of products, but also in changing the system components and the system configuration. There may be different drivers for reconfiguration: new product, changes in the product, changes in the market, and changes in the product specifications (e.g., higher precision) that require the integration of new process technology into existing systems.

The main requirements of RMSs are

- the system is designed around a part family with quick conversion of the system to produce different parts of the family

- quick reconfiguration of the system to increase productivity as market grows

- rapid ramp-up of the system after conversion and reconfiguration

- minimizing system lifecycle cost (which may be translated into making as few changes as possible)

- the system must be open-ended, so that it can be improved and upgraded with new process technology rather than replaced.

In summary, the RMS is a dynamic, evolutionary system in that its size and form (i.e., configuration) can change in response to changes in market demands (new products, their quantities and their specifications).


7. A Scenario Requiring Reconfiguration – a Second Example

The following example illustrates the dynamics of an RMS. It introduces several drivers for reconfiguration, and various **reconfiguration modes** and demonstrate how the system evolve during its life time.

Driver: New Product –> **Mode:** Design of a New Reconfigurable System for the Family. Assume that the projected annual volume of product A is between 300,000 and 400,000 parts. Traditionally, a dedicated line with capacity of 400,000 parts (namely, 1600 per day) is installed. Alternatively, an FMS (which is more expensive than the DML) with capacity of 300,000 may be built. With the RMS methodology, a system with reconfigurable machines and capacity of 300,000 parts is built and starts to operate at Year 0, as shown in **Figure 13.** Unlike FMS, the new RMS for a new product is installed just with the functionality needed for this product, and therefore is less expensive than FMS. The RMS design enables the upgrading of the system functionality when an additional new product of the same product family is introduced.
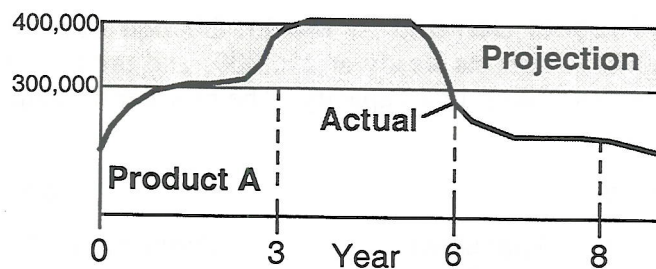
Year 0 : Design for 300,000 of Product A
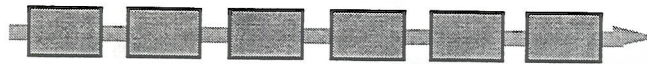
Year 3 : Increase Volume to 400,000 of Product A
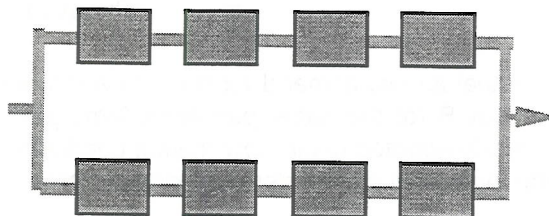
Figure 13. The annual volume projection of a product A is between 300,000 to 400,000 units. In the first phase (Year 0) the RMS is built for production of 300,000 units. As market grows (Year 3), the system configuration is changed and it is expanded to produce 400,000 units annually.

Driver: Changing Product Demand –> **Mode:** Change Capacity on Existing System
The actual demand does not exceed the planned capacity for two years. Towards the third year demand starts to accelerate. The RMS capacity is quickly upgraded by 30% to supply the additional demand. To enhance reliability, the system configuration is changed to two parallel lines (see Fig. 13). However, at the 5th year the unexpected happened – demand started to decrease and the system capacity is underutilized.

Driver: Add New Product –> **Mode:** Add Functionality
The company realized that the original product A is phasing out, and introduced a new product of the same part family. The RMS in Year 6 is changed to accommodate the new situation: Product A is phasing out and product B is ramping-up; both should be produced on the existing system. The functionality of several individual machines is upgraded to accommodate the production of product B. The new system configuration is shown in **Figure 14**. Line 1 produces 200,000 units of product A. Line 2 produces both products: 90,000 of A and 100,000 of B.

Driver: Convert between Products –> **Mode:** Reconfigure the Machines
For 50% of the time Line 2 produces product B (100,000 units annually), and for 45% of the time it produces product A. It operates as follows. For 4 hours it produces only product B. Then the line is turned off (e. g., for 30 minutes) and the machines are converted to produce product A. The machines are designed for quick software and hardware conversion and reconfiguration (e.g., manual adjustment of an angle of a drill).

Driver: Changing Product Demand –> **Mode:** Change Capacity on Existing System
The demand for product A remains steady at 250,000, and product B continues to ramp-up.
The new situation requires adding 12% capacity. The new configuration of the system at Year
8 is shown in Figure 14.
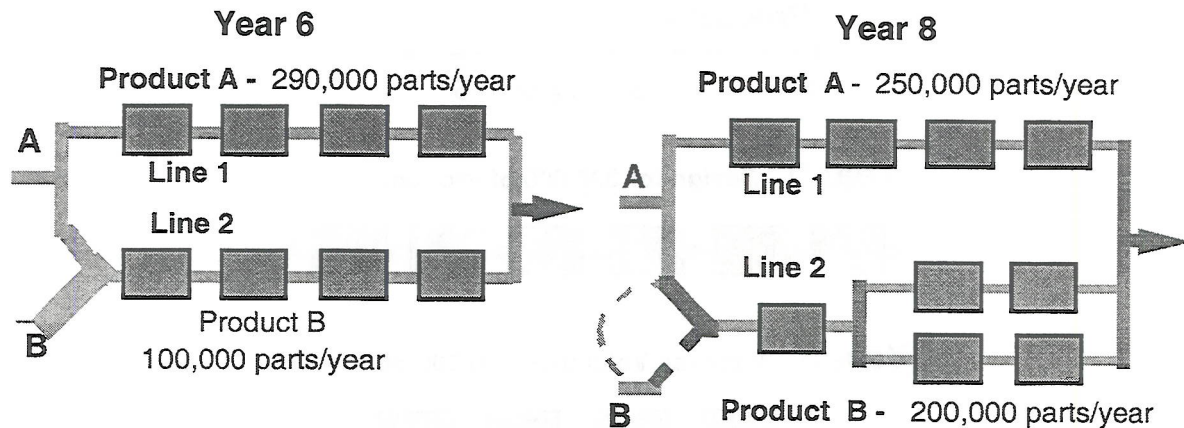
Figure 14. At Year 6 the actual annual demand for product A decreases to 290,000 units. At the
same time a product B (of the same part family emerges). The RMS configuration and
functionality is quickly adapted to the new market conditions. Capacity is added at Year 8
to respond to the increased market demand for product B.

**Driver:** Improved Quality or Productivity Requirements
Mode: Integrate New Process Technology into Existing System
A troubling problem with FMS is the high risk of an expensive flexible production system
becoming obsolete. Because advances in software, computers, information processing,
controls, and high-speed motors sometimes occur in cycles as short as one year, today's most
efficient production system can become inefficient, and even obsolete, almost as soon as it
goes on-line. This problem is avoided with RMS technology, since it enables integration of
advanced components and controls into existing RMSs.

## 8. The Economic Benefits of Reconfigurable Manufacturing Systems

Figure 15 illustrates the dynamics of the RMS in the above-described scenario. If we take
into account the entire life-cycle cost of a manufacturing system, a reconfigurable system is
less expensive than FMSs or even DMLs. As was illustrated, the RMS allows one to add the
extra capacity exactly when required (Years 3 and 8), and to add the additional functionality
exactly when needed (Year 6). Further, when product demand is decreased, the RMS capacity
can be reduced and the extra modular components may be reused to augment other lines that
have increased product demand.

An economic benefit of a different type is the enhanced productivity achieved with RMS. If
properly designed, RMS will provide the right balance between production speed and general
flexibility. Dedicated lines are *customized* hardware lines built with precisely the functionality
needed to produce a specific product. Therefore, they can take advantage of using *multiple
tools* that cut the part simultaneously (each group of tools in one direction of motion), thereby
achieving high productivity. On the other hand, CNC machines, the cornerstones of FMS,
are designed as multi-axes, general-purpose machines that use a *single tool* that can be
manipulated in different directions to allow for *general flexibility*. However, not all these
axes-of-motion are needed in the production of each part.
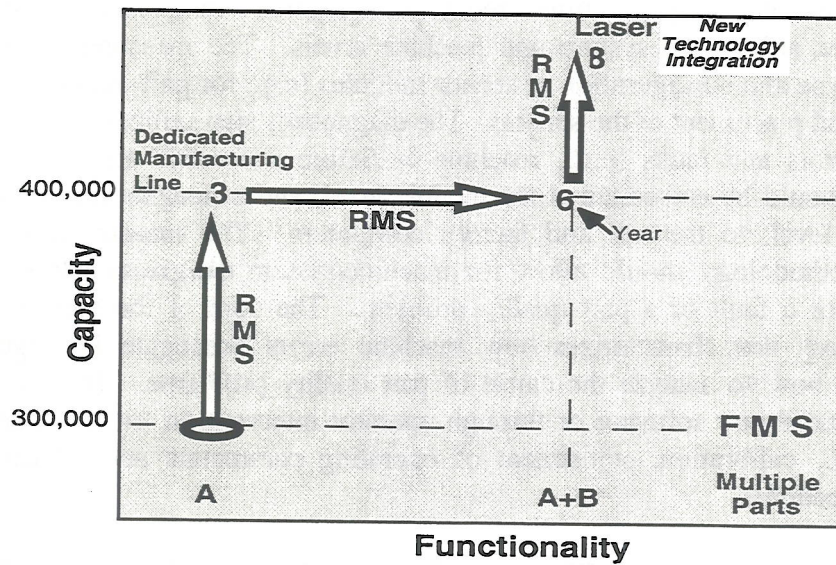
Figure 15. Mapping of three types of manufacturing systems in terms of capacity-functionality. The capacity of RMS can be quickly adapted to new market demands, and its functionality can be modified to accommodate new products.

Reconfigurable machine tools combine the high-productivity achieved with multi-tool operation with the programming ability of a CNC. A conceptual example of a reconfigurable machine that consists of a CNC base and a customized tooling unit is shown in **Fig. 16**. The tools in the tooling unit may be arranged also at different angles to machine special features. The reconfiguration from product A to product B requires a change of the tooling units on the machines.
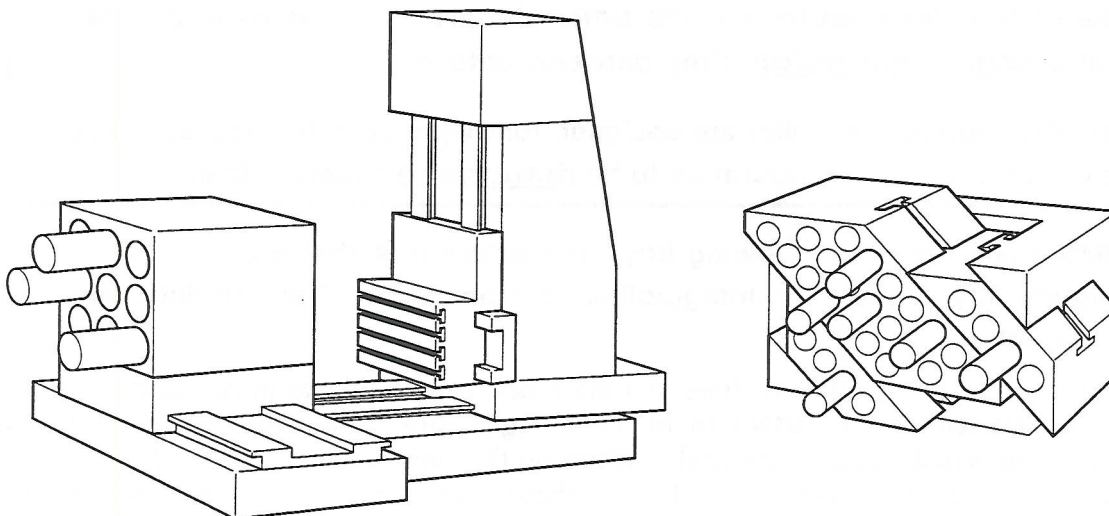
Figure 16. An RMS machine with a CNC base (concept by Y.K.; artist R. Hill 1992). Reconfiguration requires changing the customized tool modules

9. Rapid Ramp-Up of Reconfigurable Systems

The objective of ramp-up time reduction requires diagnostics and compensation methodologies, at both the system and machine levels. The measurement step requires the selection of type and configuration of sensor modules (e.g., for part dimensions, cutting force) and the optimal placement of the sensors. The diagnostics step utilizes that sensor information to identify errors and faults (e.g., machine or fixture geometric errors, or tool breakage). Diagnostics should be embedded at the module level, and propagate the information through the machine level, to the cell and factory computers. The measurement system and the diagnostic methodology should allow for machine/system **diagnosability** — identifying a sole source for a fault or a part quality problem. The core of the method is a Stream-of-Variation theory that characterizes how machine errors propagate in large manufacturing systems, and how to analyze the cause of part quality problems. The compensation step, either automatically by software or through operator intervention, enables corrective action to be taken (e.g., calibration, adjustment of operating parameters and adjustment of passive degrees-of-freedom).

10. Principles and Key Characteristics of Reconfigurable Systems

We may now summarize the principles of RMS.

- The RMS and its RMTs are *designed for reconfiguration* at the outset

- The RMS has a <u>modular</u> structure (machines, controls), with components <u>designed for integration</u> to enable reconfigurability for *scalability*, *added functionality*, and *reusability*.

- The RMS and its RMTs are designed for a *part family* with built-in <u>customized flexibility</u>

- The RMS is designed for a *cycle time*, with production done in *batches*, with a <u>short conversion time</u> between batches

- The RMT and its controller are designed for diagnostics to allow errors due to conversion & reconfiguration to be <u>diagnosed</u> systematically

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The RMS possesses the following key characteristics that enable reconfigurability: Modularity, Integrability, Customization, Convertibility, and Diagnosability.

To allow rapid reconfiguration of lines and machines, reconfigurable manufacturing systems **must be designed at the outset to be reconfigurable**. Otherwise, the reconfiguration process will be lengthy and impractical. Achieving this goal requires that a RMS possesses several key characteristics (see **Fig. 17**). These characteristics, on which we elaborate below, are common to many production domains (machining, assembly, semiconductor fabrication, and production of consumer products).
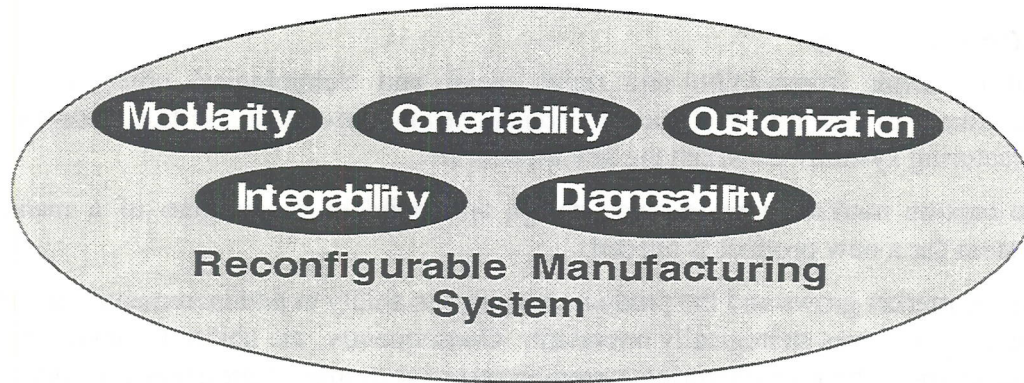
Figure 17. The design of RMS utilizes scientific knowledge to achieve certain key characteristics

Modularity: In a reconfigurable manufacturing system, all major components are modular (e.g., structural elements, axes, controls, software, etc.) and designed for integration. When necessary, the components can be replaced or upgraded to better suit new applications. Selection of basic modules, and their synthesis methodologies, must allow creation of systems that can be easily integrated, converted, and diagnosed.

Integrability: Methodologies and software tools for system integration do not exist. To aid in designing reconfigurable systems, a set of system configuration and integration rules must be developed. When the performance of each module (e.g., the stiffness of motion modules) and the characteristics of the interfaces (e.g., mechanical joints) are known, the integration methodology should estimate the performance of the whole system.

Customization: To reduce system cost, the machine and controller configuration must be customized to fit the dominant features of a part family and the application by utilizing the concepts of customized flexibility and customized control. *Customized flexibility* means that the dominant features of the part family being manufactured determine the machine configuration. Eliminating unnecessary axes of motion, for example, will increase reliability and reduce cost without compromising flexibility.

Convertibility: System switchover between product batches and the subsequent setup need to be carried out quickly to be effective. To achieve this, the RMS and its RMTs contain advanced mechanisms that allow easy conversion (and also reconfiguration) as well as sensing and control methods that enable ease of calibration of the machines after conversion (and reconfiguration).

Diagnosability: As production systems are made more reconfigurable, and their layouts are modified more frequently, it becomes essential to rapidly tune the newly reconfigured system so that it produces quality parts. Consequently, reconfigurable systems and RMTs must be designed with product quality measurement systems as an integral part. These measurement systems are intended to help rapidly identify the sources of product quality problems in the production system and to correct them by utilizing information technologies, statistics, and signal processing techniques.

These characteristics determine the ease of reconfigurability of manufacturing systems:

- **A system that possesses these key characteristics has a high level of reconfigurability.**
- **A system that lacks these key characteristics cannot be cost-effectively reconfigured.**

[Can any metrics for those characteristics be quantified based on examples? E. g., scalability resolution, or number of modules to be changed during conversion.]

11. Conclusions

Global economic competition and rapid social and technological changes have forced manufacturers to face a new challenge: *manufacturing responsiveness* (i.e., adaptation of the manufacturing system), of which the key aspects are:

- To capture market share, a quick design and build or reconfigure of a manufacturing system for a new product is needed.

- As the market grows and the product changes, the ability to add incremental manufacturing capacity becomes strategically important. Consequently, the ability to rapidly reconfigure and augment the manufacturing system in response to market pressures is critical.

- Manufacturing technologies are developing rapidly, and new technologies need to be incorporated into the manufacturing system to cost-efficiently maintain quality and productivity. Consequently, the ability to integrate new manufacturing technologies and new components into the manufacturing system as they become available is significant in competing for market share.

To respond to these key manufacturing issues a new type of manufacturing system, a *Reconfigurable Manufacturing System* (RMS) is needed. RMSs are quite different than the current flexible manufacturing systems – they are dynamic systems that evolve in their capacity and functionality in response to market demands exactly when needed. The vision of a RMS is a living factory that evolves over time as new technology and products are introduced and product demand changes.

Acknowledgments

References
1. Pine B. J.: *Mass Customization,* Harvard Business School Press, 1993.

2. Koren Y.: *Computer Control of Manufacturing System,* McGraw-Hill, 1983.

3. Mehrabi, M., and. Ulsoy, G. (eds.): *State-of-the-Art Review of Technologies Related to Reconfigurable Manufacturing,* ERC/RMS Technical Report #2, University of Michigan, Ann Arbor, Michigan, October 1997.

4. Koren, Y.: Cross-coupled computer control for manufacturing systems. *Trans. ASME J. of Meas. Dynamic Systems. and Control,* Vol. 102, No. 4, pp. 265-272, December 1980.

5. Koren, Y. and Lo, C.: Variable-gain cross-coupling controller for contouring. *CIRP Annals,* Vol. 40, No. 1, pp. 371-374, 1991.

6. Koren, Y. and Lo, C.: Advanced Controllers for Feed Drives. (Presented as a keynote paper.) *CIRP Annals,* Vol. 41, No. 2, pp. 689-698, October 1992.

7. Koren, Y., Pasek Z., Ulsoy G., and Benchetrit U.: Real-Time Open-Control Architectures and System Performance. *CIRP Annals,* Vol. Vol. 45, No. 1, pp. 377-380, July 1996.