The Rapid Responsiveness of RMS

Yoram Koren

JJ Duderstadt Distinguished University Professor of Manufacturing

The University of Michigan, Ann Arbor Michigan, U.S.A.

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Abstract

Manufacturing enterprises are facing in the last decade unpredictable market changes driven by global competition. To stay competitive, these enterprises must possess new types of manufacturing systems that can rapidly respond to market changes. Reconfigurable manufacturing systems (RMS), which were invented in the mid-1990's, are characterized by their rapid and cost-effective response to market changes, and therefore are frequently being built by global enterprises. The RMS components are CNC machines and some reconfigurable machines that are all connected into a system in way that enables changes in the system structure to accommodate new product types and their desired volume. Methodologies for the systematic design for rapid system modifications while maintaining consistent product quality are the cornerstones of the RMS paradigm.

Keywords: reconfigurable manufacturing systems; RMS characteristics; system design

1. Introduction

Until the 1970's cost reduction was the premier goal of manufacturing enterprises. It was only in the 1970's that the Japanese industry demonstrated that products with higher quality do not necessarily cost more to produce. Producing high quality products at low cost became a major goal of the Western manufacturing industry since the 1980's. In the early 1990's the author predicted that globalization would become a major factor in industrial competition, and therefore designing manufacturing systems with the ability to respond rapidly to market changes will become a vital goal for the industry. At that time almost all the production systems in the global powertrain industry (e.g., producing engines, transmissions, etc.) were dedicated transfer lines that could produce only a single product at low cost when produced at very large quantities. These dedicated lines could not be changed to produce a different product. Therefore, we suggested at that time to add manufacturing **Responsiveness** to the traditional goals of Low Cost and High Quality products (Figure 1). Modern manufacturing systems are designed to achieve the three goals simultaneously (Koren and Ulsoy 2002).

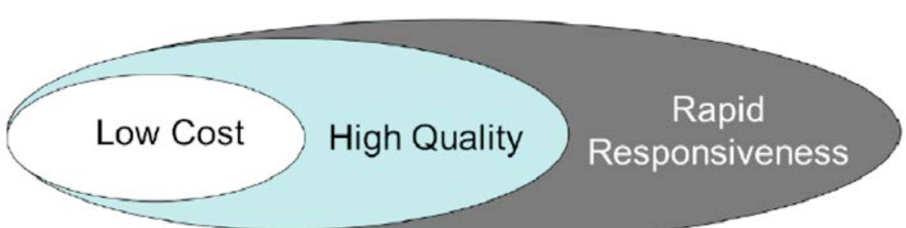

Figure 1. Three major goals guide the manufacturing industry

In 1994 the author led a team from academia and industry that proposed to the NSF to form a national center for designing systems that could be rapidly changed. In 1996 the Engineering Research Center for Reconfigurable Manufacturing Systems (ERC-RMS) was formed at the University of Michigan and operated until 2010 with financial support of $47 million from the NSF, the state, and major manufacturers (General Motors, Ford, Chrysler, Cummins, Caterpillar, Boeing, and machine tool and control companies). The Center was granted 12 US patents on RMS technologies, had 9 technology implementations in automotive plants, provided financial support to 72 Ph.D. students who developed RMS technologies, and published 1,700 papers that acknowledged the Center support.

The compelling motive to form the Center was the need of the industry to cope with unpredictable market changes that are occurring at increasing pace. These market changes included: (1) Short windows of opportunity for introduction of new products, (2) Large fluctuations in product demand, and (3) Large fluctuations in product mix. These drivers reflect a new balance among global economy, society and technology. To gain profit in this new environment, manufacturing companies must be able to react to changes **rapidly** and **cost-effectively.**

To be responsive to markets, two basic types of reconfiguration capabilities are needed in manufacturing systems – in their functionality and in their production capacity. Adjusting the system production capacity is needed in order to cope with fluctuations in product demand (and mix) caused by changing market conditions. Figure 2 shows how the actual demand for Products A and B can be different from what was planned (initial projection).

Therefore, the strategic goal of the center was to develop a **responsive** manufacturing system that is designed for rapid and cost-effective changes (Koren and Ulsoy 1997). Its production capacity must be rapidly **scalable** to produce more products on existing systems exactly when the market needs them. The system must be also easily **convertible** from one product to another that customers like more. These manufacturing requirements are expressed by our slogan:

" … exactly the capacity and functionality needed…. exactly when needed."

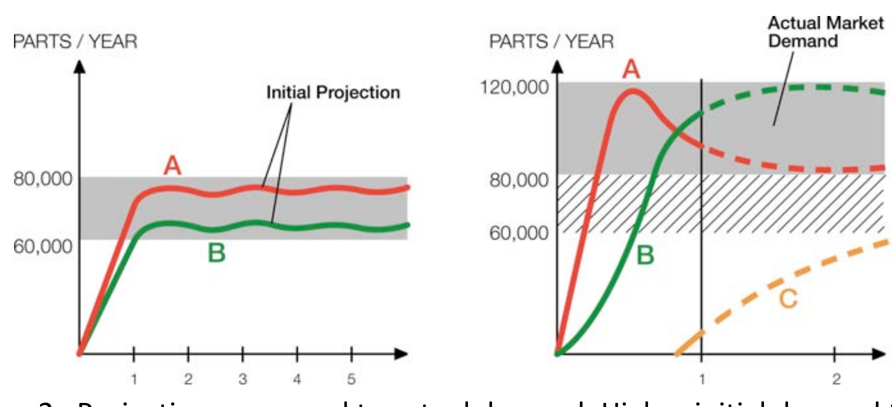

Figure 2. Projection compared to actual demand: Higher initial demand than expected for both products and Product C is introduced earlier than expected

2. Practical RMS Configurations

The production in large manufacturing systems is done in many stages. In these multi-stage systems product is partially processed in one stage and then transferred to the next until all operations are completed. The configuration of a system can facilitate or impede the system's productivity, responsiveness, convertibility and scalability. Multi-stage manufacturing systems can allow for several practical configurations depending on (1) the way the machines are arranged in the stages, and (2) the way the machines are connected via the material handling system (Spicer et al, 2002).

The first step in designing a new system is to determine the number of possible configurations when the daily demand, *Q* [parts/day], and the total machining time for the part, ***t*** [minute/part], are given. The **minimum number of machines,** *N*, needed in the system is calculated by the equation

$$N = \frac{Q \times t}{Minutes/day\ available \times Machine\ reliability} \quad (1)$$

We assume 100% reliability of all pieces of equipment (i.e., machine reliability = 1). The resulting number of machines calculated by Eq. (1) must be rounded to the next larger integer. For example, if there is a need for 500 parts per day, and the processing time for each part is 9.5 minutes, for a working time of 1000 min/day there is a need for at least five machines in the system. The system designer should determine what is the best way to arrange these five machines and how to connect them. This decision is challenging because the five machines, can be arranged in many configurations, 33 of which are shown in Figure 3. The designer's dilemma is which one of all these configurations is the most advantageous?

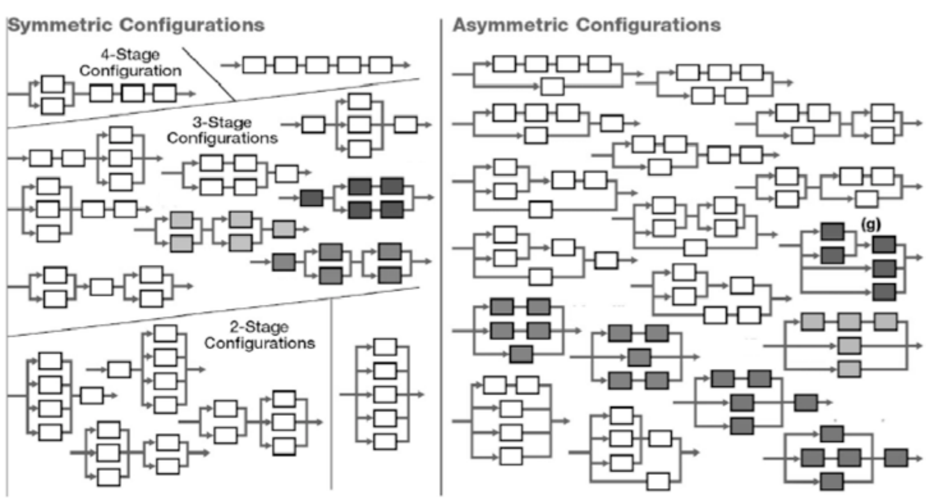

Figure 3. Configurations with 5 machines

In the general case the total number of configurations for *N* machines is huge. When plotted on a logarithmic scale, the number of configurations increases almost linearly with the number of machines. For example, in the case of five machines the total number of possible configurations is 48. Six machines can be arranged in 170 configurations, and 10 machines can be arranged in over 35,000 configurations. In the powertrain industry the number of machines in one system may be over 100 machines. Nevertheless, practically only symmetric configurations are suitable for manufacturing systems (Koren 2010), and therefore the number of possible practical RMS configurations is much smaller.

Symmetric configurations may be of three basic classes that are shown in Figure 4. (I) Several serial manufacturing lines arranged in parallel. (II) RMS Configurations that always have crossover connections after every stage. The part from any machine in stage *i* can be transferred to any machine in stage (i + 1). All machines and operations in each stage are identical. (III) Configurations in which there are some stages with no crossovers. This class includes combinations of the previous two classes.

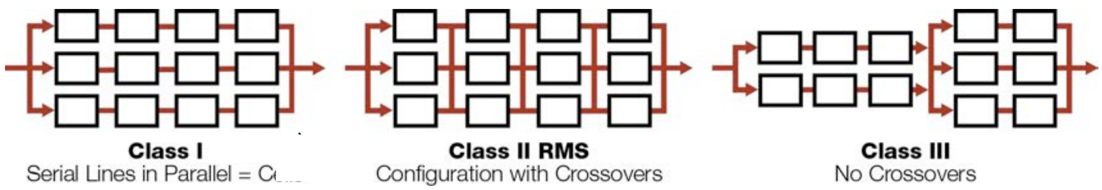

Figure 4. Three classes of symmetric configurations

Methods for selecting the optimal configurations were suggested by Goyal et al (2012), by Xiaobo et al. (2000b), and by Li et al. (2012) who suggested a method based on Petri nets. These methods, however, are difficult to implement in practical cases. A systematic methodology to design configurations when the number of machines is given was presented by Koren and Shpitalni (2010). A simple example of a practical RMS configuration is depicted in Figure 5. It represents a system already being utilized in the powertrain industry in North America. It is a system of three stages that can produce two different parts (a and b) simultaneously. A cell gantry serves all machines in a particular stage; it brings parts and loads them on the machines, and takes the finished parts and transfers them to a buffer (the circle in Figure 5) located next to the main material handling system. The latter is usually a gantry (called the spine gantry), but it can be also a conveyor, or several AGVs. To balance the system sequence, all stages should have almost the same cycle time. The machines in each stage are always identical. In Figure 5, the cycle time of each of the two machines in Stage 2 is approximately 1.5 times shorter than the cycle time for the three machines in Stages 1 and 3. (In industry, the set of all machining tasks assigned to a stage is called an “Operation”.)

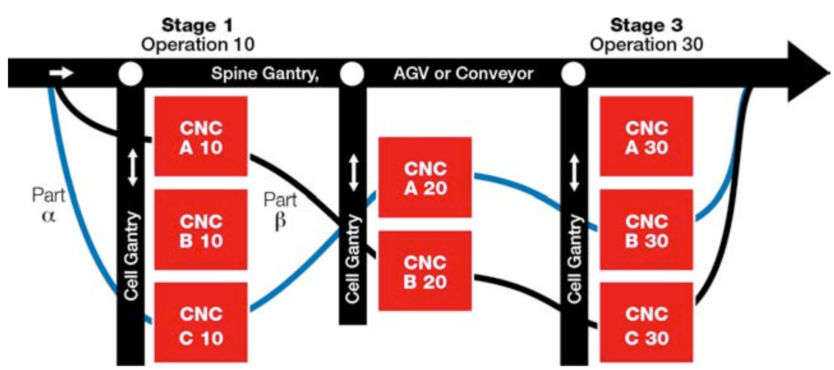

Figure 5. Practical RMS configuration with three stages

3. RMS Key Characteristics

A Reconfigurable Manufacturing System (RMS) is a system designed at the outset for rapid changes in its structure, as well as in its hardware and software components, in order to quickly adjust the production capacity and functionality within a part family (Xiaobo et al, 2000a). Example of a change may be adding a CNC machine to stage 2 in Figure 5, which also requires extending the cell gantry to serve the new machine.

The reconfigurable systems must be designed for several changes during their lifetime, and must be created by using hardware and software modules that can be integrated quickly and reliably. If the system and its machines are not designed at the outset for reconfigurability, the reconfiguration process will prove lengthy, and therefore impractical. Achieving this design goal requires that the RMS possess the six key characteristics listed below.

Scalability is the characteristic that enables to design the system structure for changes in order to modify its capacity in response to market demands. Changing capacity means changing the production volume per day. Structure may be adjusted at the system level (e.g., adding machines), and at the machine level (e.g., adding spindles, adding axes, or changing tool magazines).

Convertibility is defined as the capability of a system to adjust production functionality, or change the system from one product to another of the same product family. System convertibility includes contributions due to machines, their arrangements or configuration, and material handling devices. End-users of manufacturing systems are struggling with the issue of how to measure and quantify convertibility. Metrics for convertibility were proposed so that different manufacturing systems can be compared with respect to this area of performance (Maier-Speredelozzi, 2003). These metrics are based on assessments of the configuration itself, and the system components such as machines and material handling devices. Metrics for quantifying convertibility are useful for comparing system configurations during the early phases of design, without requiring detailed product or process plan information.

Diagnosability in RMS means that the system is capable of being rapidly diagnosed, in order to reduce the reconfiguration ramp-up time. Diagnosability enables identifying rapidly the sources of bad quality products after reconfiguration. Detecting unacceptable part quality is critical in reducing the ramp-up time that is needed after each reconfiguration. Diagnosability is performed by adding in-line inspection machines in the system to identify inaccuracies, and using a method that enables identifying the source of the error, namely performing root-cause analysis in real-time during production. As production systems are reconfigured more frequently, it becomes essential to rapidly tune the reconfigured system so that it produces quality parts. Therefore, built-in diagnosability is an essential property of RMS.

Modularity. In order to reduce the reconfiguration time in a reconfigurable manufacturing system, all major components should be modular (e.g., designing a gantry composed of modules enables extending the gantry to serve an additional machines).

Integrability is a characteristic that aims at reducing the reconfiguration cost and time. Designing hardware and software interfaces for quick module integration with other modules reduces the reconfiguration time.

Customization is a characteristic that aims at reducing the reconfiguration cost. It is accomplished by designing a manufacturing system around the part family (Zhang *et al.* 2012), with the customized flexibility required for producing all parts of this part family (Koren *et al.* 1999, Dou *et al.* 2010). Therefore, the definition and formation of part families are essential to RMS design and operations (Kapil *et al.* 2012). The formation of a product family may sometimes be determined by product-process simultaneous reconfiguration (Abdi, 2012), which further may reduce capital cost.

The six key RMS characteristics determine the ease and cost of reconfigurability of manufacturing systems, and thereby enabling rapid responsiveness of the enterprise to sudden market changes. But, as seen in Figure 6, the six characteristics contribute also to the other goals of the enterprise: Low cost and high quality products.

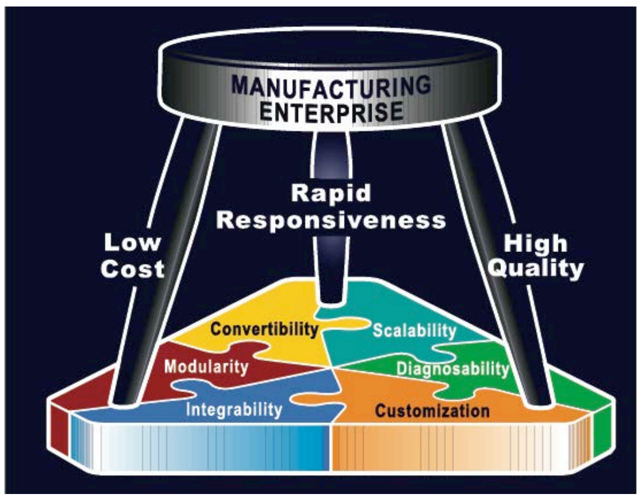

Figure 6. The goals of 21st Century manufacturing enterprise are
High Product Quality, Low Cost, and Rapid Responsiveness
that are grounded on six RMS characteristics

Designing a system that contains the six characteristics enables accomplishing three goals:

1. Achieving “exactly the capacity and functionality needed, exactly when needed.”
2. Reducing the time for reconfiguration.
3. Reducing the cost of reconfiguration.

Two of these six RMS characteristics —Scalability and Diagnosability— were identified by our industry partners as critical to achieving cost-effective responsiveness in their plants. We would like to elaborate below on these two characteristics.

4. Scalability Accommodates Future Surge in Demand

Scalability of the system’s production capacity is the ability to quickly and cost-effectively change the system capacity (i.e., the possible maximum production volume). Scalability is accomplished by adding (or subtracting) manufacturing resources to an existing system (e.g. machines, spindles, gantry modules, etc.). In order to achieve a rapid and cost-effective scalability, the system has to be designed at the outset for scalability, which may require some additional capital investment when the system is originally built (Wang et al 2012).

An example of scalable system configuration is depicted in Figure 7. Producing a part requires 21 tasks, that each requires 30 seconds, namely 630 seconds are needed to produce each part. In this case each of the six machines in the system does seven tasks of 30 s each, totaling 210 s per machine, and the system produces a part every 1.75 minutes (274 parts per 8-hour working day).

When the demand grows from 274 to 320 parts/day, seven machines are needed (320: 274=7:6). This is accomplished by adding a new machine to Stage 2 as shown in Fig. 7b. The last task that was performed on Stage 1 is shifted from Stage 1 to Stage 2 (so each machine in Stage 1 operates for 180 s on the part), and the first task that was performed on Stage 3 is shifted from Stage 3 to Stage 2. Two tasks were added to Stage 2, so each machine in Stage 2 will now operate for 270 s on each part, and the system cycle time becomes 90 s per part. Now the system produces a part every 1.5 minutes. A perfect scalability has been obtained.

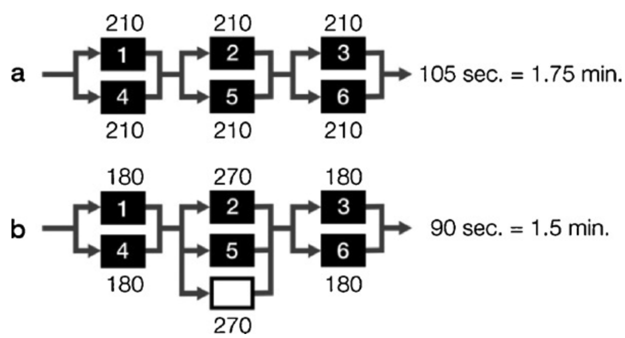

Figure 7. When demand grows, the initial system, **a**, is scaled-up to Configuration **b** to meet the new demand

We were asked by an auto company to design a machining system for future increase in its production volume, i.e., design for scalability. The system was composed of three stages with four CNC machines at each stage (total 12 CNC machines). The part required many unequal machining tasks, and therefore a rigorous line-balancing algorithm must be utilized to balance the operation time in each stage, both for the present time and for the future, after scalability when demand grows. Balancing algorithms are essential to system scalability, and may be based on heuristic approaches (Dolgui 2005, Essafi *et al.* 2012), or on Graph Approach (Dolgui 2006).

Our line-balancing algorithm, however, is based on Genetic Algorithm. The two planned possible future scalability steps were adding 8% and 16%, which obviously should be accomplished by adding one machine and two machines, respectively. The design challenge is in which stage to add the first machine, and where to add the second machine. The solution requires extensive programming using a line-balancing algorithm. The results are shown in Figure 8. For the first scalability step the line-balancing calculations show that adding a machine in the third stage will result in the maximum throughput gain. The unexpected result in this case is that for the second scalability step the second machine should be also added in stage 3.

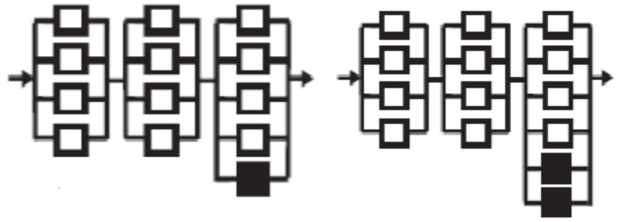

Figure 8. A case study of an RMS with two scalability steps

Building a system for future scalability requires additional capital investment. In the case of Figure 8 we have to reserve one spot, or two spots, in Stage 3 for the option of adding one, or two machines if needed in the future. It is also optional to extend the cell gantry (which is built on the ceiling) for the option of serving these two machines. These options (reserving space, and extending the gantry) require additional cost, which is very small compared to the total system cost, but, in turn, guarantees rapid scalability if needed. If scalability is performed quickly exactly when needed, the manufacturer profit increases enormously.

The extra capital investment needed for quick scalability is similar to buying an insurance premium for a future event, which is likely to occur. In our case, if the demand does rise, new machines should be purchased and the system can be rapidly scaled up to supply the new demand in a short time. If the demand is unchanged during the lifetime of the system, a small capital investment on the space reserved and the extended material handling system was lost. The financial consequences are similar to buying car insurance and not having an accident.

So far we discussed scalability at the system level. However, scalability may be also performed at the equipment level. For example, it was shown that cost-effective volume scalability is achieved by utilizing modular scalable machine tools. The cost-effectiveness of such machines can be numerically evaluated, as well as the calculation of the optimal number of modules that can be included in scalable machines [Spicer et-al, 2005].

5. Diagnosability Enables Rapid Ramp-Up

Rapid ramp-up of a manufacturing system after installation, as well as after each reconfiguration enhances responsiveness and reduces cost, and therefore is essential to the success of the RMS paradigm. As production systems are made more reconfigurable, and their functionality and layouts are modified more frequently, it becomes essential to rapidly tune the newly reconfigured system so that it can quickly produce quality parts. If ramp-up is not done quickly, the reconfiguration advantage is lost. The Ramp-Up period is defined as:

Ramp-Up Period is defined as the period of time it takes a newly introduced system or a reconfigured manufacturing system to reach its designed levels of production in terms of both throughput and part quality.

A system with built-in **diagnosability** enables rapid ramp-up and high yield (i.e., producing good quality products). Diagnosability in large multi-stage manufacturing systems consists of two essential elements: (1) Measurement stations that are embedded in the system and measure features of the product at the line speed, and (2) Systematic methodology for root-cause analysis of part quality problems detected by the sensors in the measurement stations; the methodology should identify the sole cause and source of the detected fault.

For example, the measurement stations in an auto-body assembly line can detect faults such as a broken locator, or incorrectly programmed robot. If these manufacturing problems are not diagnosed and fixed, they can lead to problems in subsequent assembly, and eventually to quality problems in the final product, such as wind noise and water leakage. Note that a typical auto-body assembly line has 100 to 150 sheet metal parts that are welded in 100 serial assembly stations. The auto-body has about 1500 to 2000 fixture locators and approximately 4000 welding spots. So the probability that something will be assembled with errors is large. Only systematic in-line diagnostics methods can identify errors in real time.

When building the diagnosability characteristic into the system, the designer has to resolve the following issues:

- How to systematically find the root-cause of errors, in terms of which manufacturing machine/station introduced the error?
- How to distribute the measuring stations for effective diagnostic control?
- What to measure on the workpiece at each intermediate measurement stations?

To achieve diagnosability, we developed a method called Stream-of-Variations [Hu 1997], and a reconfigurable inspection machine (Koren and Katz, 2003). The Stream-of-Variations (SoV) method utilizes state space model to describe the variations and their propagation. In control theory the discrete state-space method has discrete time as the variable. In the SoV method for a serial line the discrete variable is the machine position in the line. SoV combines engineering process models with statistical analysis to account for how product dimensional variations accumulate as the product moves through a manufacturing system. It can be used, with appropriately selected and placed sensors, to diagnose the root causes of dimensional errors in the production system. Details are given in a book written by Shi (2006).

The enormous advantage of the SoV method is demonstrated in Figure 9, in which data points from actual production of auto-body assembly have been plotted. This figure proves the advantage of the systematic ramp-up process with built-in diagnosability. Applying the SoV reduces the error ("variation") more rapidly (15 weeks sooner than without SoV in this case), and more effectively, reducing auto-body variations from 5 mm to 2.2 mm. These improvements translate into a significant time-to-market advantage with huge benefits to the manufacturer, and a better product for the consumer (for example, doors that perfectly fit their opening, and trunks that close more accurately).

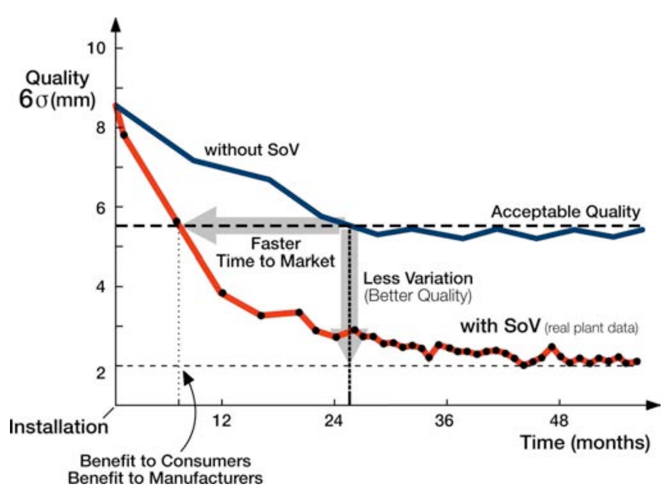

Figure 9. Results showing ramp-up time reduction in automotive body assembly

An implementation of our reconfigurable inspection machine is shown in Figure 10. It is an inspection machine that is based on machine vision to detect small surface pores on the surface of engine blocks. High-resolution images of the engine block surface are acquired using a computerized vision system. The images are then analyzed to detect and measure pores (small pits < 1mm on the surface resulting from casting). In 2006 General Motors installed our in-line surface porosity inspection system at its Flint, Michigan engine plant. The inspection system was integrated into the production line, with a conveyor moving all engine blocks through this station. Using our technology GM prevents defective parts from reaching customers. Before our RIM was installed, an operator visually inspected each block at the line rate (20 seconds/engine block).

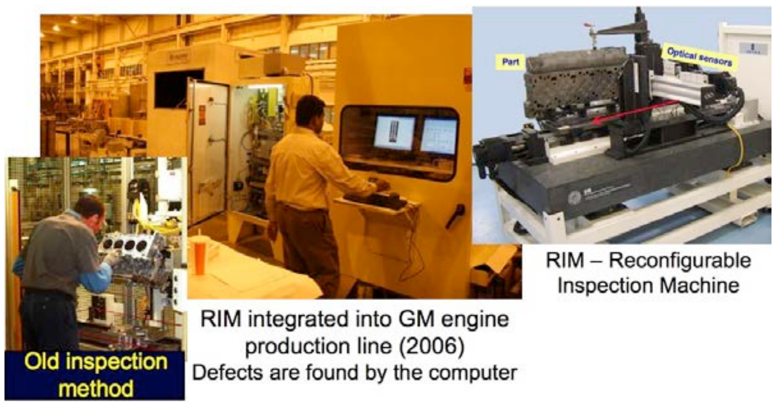

Figure 10. The reconfigurable inspection machine detects pores on engine blocks

6. Futuristic RMS Configurations

To increase the productivity of the system, Reconfigurable Machine Tools (Koren and Kota, 1999) may be integrated into the RMS. Figure 11 shows an RMS incorporating two specifically designed RMTs in Stage 2. One RMT is capable of producing part α, and the other RMT produces part β, both parts at the same time. In a more sophisticated RMT, the spindle heads are on a 90-degree index table that rotates to fit the part entering for processing, and then there is a need for only one RMT. The index-type spindle head can accommodate up to four different parts and there is no need to employ multiple RMTs. Another alternative may be a transfer machine that is built around a rotary (Dolgui et al, 2009) table that may be installed in Stage 2.

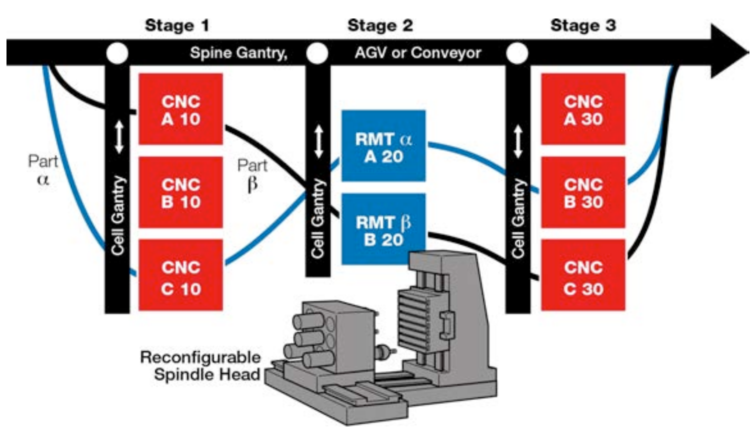

Figure 11. RMS with integrated reconfigurable machine tools (RMT)

The configuration in Figure 11 possesses five core characteristics, but it does not contain in-process measurement stations to monitor product quality that are needed for diagnosability. To accomplish the latter task, reconfigurable inspection machines (RIMs) must be integrated into the system in sequence with the part flow, such that they are part of the system configuration.

An important issue is what happens if the RIM is down? The last thing that a plant manager wants is for an inspection machine to stall production. The solution — install the RIMs as a separate stage that allows the inspection to be conducted in a contaminant-free environment and can be by-passed if necessary. This solution is depicted in Figure 12.

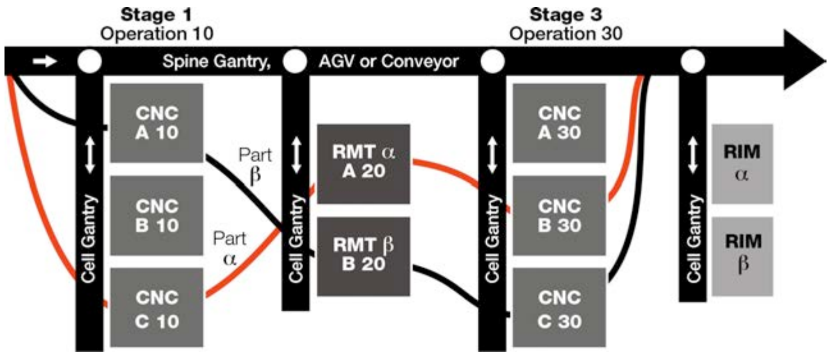

Figure 12. RMS with integrated RMTs and RIMs

We have now a perfect RMS that possesses all six characteristics. But is this RMS truly perfect? What happens to the bad parts that the RIM tagged to be sent back for reprocessing? Or, what happens if, for example, CNCs B30 and C30 are both down and the productivity is reduced by 66%? Is there an alternative to reducing productivity to only 33% throughput in this case?

In order to improve the system responsiveness in these two cases, we can add a return conveyor (or an AGV line, or a gantry) to move the parts backwards, as depicted at the bottom of Figure 13. Bad parts can be sent for reprocessing at any stage. In the case of both CNCs in the third stage being down for an extended period of time, CNC C10 can be reprogrammed to share the load. After the drilling operations at Stage 2, the part can be sent back to CNC C10 to perform the tasks of Stage 3. We have now the ideal RMS – very productive with in-process quality checks, and highly responsive to both customer's needs and machine failures.

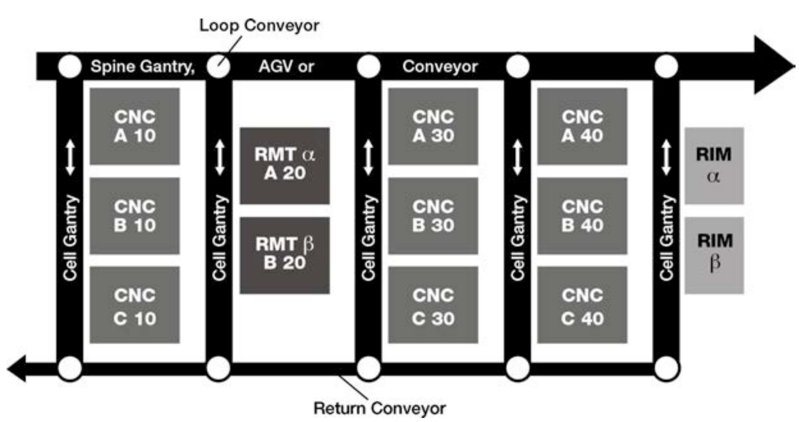

Figure 13. Proposed RMS with integrated RMTs and RIMs and a backwards flow-path

6. Conclusions

With the recent increase in consumer demands for a wider variety of products in unpredicted quantities, manufacturing system responsiveness has become essential for industry competitiveness. To stay competitive in the 21st Century manufacturing enterprises must possess manufacturing systems that can be rapidly adjusted with regard to both functionality and throughput capacity over the lifetime of the system.

Reconfigurable manufacturing systems (RMS) are characterized by their rapid, cost-effective response to market changes. The RMS components are CNC machines and some reconfigurable machines that are all connected into a system in way that enables changes in the system structure as the market demands. To build an ideal RMS, six characteristics have to be embedded in the system structure: Scalability, convertibility, diagnosability, modularity, integrability and customization Of these six, scalability and diagnosability, were identified by industry as the essential characteristics that enable successful reconfigurations to seize rapidly market opportunities. These two characteristics complement each other since scaling-up an existing system to cope with changing demand requires a subsequent ramp-up period that can be reduced dramatically by implementing the diagnosability characteristic. Some highlights elaborating on the challenges in implementing these two characteristics were demonstrated. Finally, futuristic reconfigurable systems that are more efficient than the existing industrial systems were suggested in this paper.

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