The NSF Engineering Research Center for Reconfigurable Manufacturing Systems: A Director's Retrospective

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1. *What did you find **intellectually rewarding** about the position?*

In my 1995 ERC proposal I elaborated on designing a new type of manufacturing system that would have a structure that is easily adaptable to unknown future market changes. In the proposal I coined the term Reconfigurable Manufacturing Systems (RMS) and spelled out five reconfiguration principles that would allow efficient system reconfiguration. As the ERC-RMS director during the entire NSF-funded phase of the Center and for several years post-"graduation" (1996–2012), what I found to be most intellectually rewarding was: (1) establishing the mathematical base of design and operation of RMSs; (2) developing three original software packages based on our original mathematical tools, which support the design and operations of RMSs in factories; and (3) designing and building three full-size prototypes of original machines that revolutionized the state-of-art in production engineering, particularly in real-time engine inspection at the line-speed. Most rewarding of all, however, was that our scientific methods, software, and inspection machines were implemented and improved productivity **in 69 production lines in 15 factories** in the U.S. and Canada (e.g., Chrysler Mack Avenue Engine Plant, Ford Windsor Engine Plant, GM Flint Engine Plant, Boeing Everett Operations in Seattle, and Cummins engine plant, Columbus, Indiana.) It is certainly rewarding for an academic to see U.S. factories built and operated based on the RMS principles and the RMS original mathematical tools. As Mr. Richard Chow-Wah, VP at Chrysler, told me: "You bring science to the factory floor."

The concept of reconfigurability goes beyond manufacturing. In our 1998 NSF site visit, Paul Sheldon, an industry representative, explained reconfigurability to the site-visit team: *"Suppose that you are unmarried and you want to design your future house. You are sure that in the future you'll be married and have at least one child. Although you are not sure how many more kids you'll have, you are certain that you won't have more than four. Based on the reconfiguration principles, the design of your new house is: Build a house for 3—you, your wife, and a child—but design it with options to add **cost-**effectively and gradually 3 more rooms. You design the house at the outset for several subsequent stages of expansion, and therefore each house-expansion will be (a) **inexpensive**, and (b) completed in a **short time**."* In other words, to accommodate market surges, the RMS is designed with options for upgrading its output volume rapidly and cost-effectively.

2. *What was your ERC's **most important impact** and why?*

The ERC-RMS initiated a new area within manufacturing engineering that offers an engineering solution to unpredictable market conditions and therefore has had a huge impact on both industry and academia. We pioneered the implementation of scientific methods in the metals industry to (1) reduce the time to market, (2) implement changes in production systems rapidly and cost-effectively, (3) improved productivity of existing production lines, and (4) enhance product precision and quality at low cost. Consequently, RMS allows U.S. factories to lead in competing markets.

Academically, we introduced Reconfigurable Manufacturing Systems as a new, worldwide field in production engineering. In 1998 the NSF site-visit team asked why RMS was not known internationally. In response, I assembled a team of scientists from five countries (U.S., Japan, Italy, Germany, and Belgium) to write a joint keynote paper entitled "Reconfigurable Manufacturing Systems," which I presented at the CIRP 1999 General Assembly.[1] Today this keynote paper has over 2,000 citations, which makes it the highest cited of all CIRP papers—and it opened RMS as a new international research discipline that is supported by national agencies in Europe, China, and South Africa. Per Google Scholar in 2018, there are 11,000 papers that focus on RMS in the mechanical and food industries. In 1995, before the ERC-RMS was established, there were none. It is a notable impact in the academic world.

3. *What was the most challenging aspect of leading your ERC?*

A major challenge in leading the ERC was to bridge the research traditions of a conservative industry with our academic research aimed at implementing scientific methods for system design and operations, as well as in-line rapid inspection, in the traditional mechanical metals industry.

The ERC-RMS had an influential Technical Advisory Board composed of leaders of 20 ERC supporting companies. Mark Tomlinson (VP Lamb, the largest dedicated line supplier to the auto industry in the 1990s) chaired this committee in 2001. An item from Mark's presentation to the NSF site visit panel that year elaborates on this challenge:

> *"The ERC-RMS creates a working environment for creative thinking, which impacted a slow-moving industry."*

4. *What gave you the most satisfaction?*

Bringing scientific methods and high-tech tools to the traditional factory floor, which contributed significantly to **product quality** and **production efficiency.** Experts believe that the implementation of RMS technologies in U.S. automotive factories greatly assisted in the remarkable recovery of the U.S. automotive industry in 2010 and after.

Preparing and mentoring next-generation academic and industry leaders. Examples: Dawn Tilbury (today NSF's Assistant Director of Engineering) and Jack Hu (today VP Research at the University of Michigan) both began their involvement with the ERC-RMS as project directors. Both were later promoted to Thrust Area Leaders and participated in the ERC Management Committee that I chaired, learning how to manage large-scale research programs. Our Ph.D. graduate Burak Ozdoganlar is now an endowed chair Professor at Carnegie Mellon University. Burak was the President of the ERC-RMS Student Leadership Council, and in 1999 he led the team that wrote a chapter on Student Leadership Councils for the NSF's *ERC Best Practices Manual*. The title of our Ph.D. graduate Patrick Spicer is "Chief Technologist, Reconfigurable Assembly Research at General Motors," which shows how deeply rooted RMS is now in the U.S. auto industry. Our Ph.D. graduate Farshid Asl is Vice President at Goldman Sacks, heading the Strategic Asset Allocation team, where he is responsible for modeling and analysis of strategic

[1] CIRP is the International Academy for Production Engineering, with headquarters in Paris.

asset allocations. (The mathematical base of taking calculated risk in designing RMS system architecture for future market changes is similar to that of strategic investments in the finance industry).

5. *What would you rather **not** have had to do?*

I would have preferred not to have to deal with irrelevant, rude comments by some NSF reviewers (several of whom were Assistant Professors), to which we had to respond respectfully.

6. *Of the things you learned, what has stayed with you the most over the years since?*

(1) I learned how to lead by combining top-down strategic direction integrated with bottom-up scientific solutions. First, I defined to the ERC professors the strategic research direction in each Thrust Area and its central projects, defining WHAT to do to accomplish the ERC mission (i.e. top-down direction); the professors then had to work out the scientific methods and technologies aimed at HOW to accomplish the given task (i.e., bottom-up solutions).

(2) I defined a very efficient way to effectively coordinate a large-scale research program with many different players: (a) Industry end-users (the auto, aerospace, and engine production industries); (b) Industry suppliers (manufacturing systems, machines, controls, software); (c) Academic researchers from four disciplines: Mechanical, Industrial, and Electrical Engineering, and Computer Science; and (d) A large student body of graduate and undergraduate students from four engineering departments. We were the only ERC in which 30 graduate students were sitting in one open space, so they could learn first-hand what their student fellows were working on.

(3) The 3-level strategic planning diagram that Lynn Preston introduced was an excellent management tool to keep the ERC mission on track with creating new scientific methods and transferring them to the factory floor.

(4) Our ERC was very effective in introducing scientific methods and high-tech equipment to the conservative auto industry, and the implementation of our scientific tools played a vital role in the economic recovery of the US automotive industry in 2010 and after.

ADDENDA: The following information is included to expand upon and further validate my retrospective comments

ERC-RMS Funding and Operations

	Years	Funding
ERC-RMS Operations	1996–2012	$47 Million
NSF Support	1996–2007	$33 Million
Industry discretionary support	1996–2010	$10 Million
The State of Mich, DoE, DoD	1996–2007	$4 Million
Number of production lines and factories impacted	1998–2011	69 production lines in 15 factories, Chrysler, GM, Ford, Boeing, Cummins
Number of US patents	1997–2012	12 patents
Number of Ph.D. graduated	1997–2012	70 Ph.D. students, of which 12 became professors
Number of Ph.D. students advised by Assistant Profs.[2]	1997-2007	30 Ph.D. students

Industry provided additional support by donating equipment and thousands of hours of engineering time spent by industry engineers at the ERC-RMS testbed on operating prototypes, and by participating in classes teaching the ERC-software packages: PAMS, SHARE and the Life-Cycle Cost Model.

[2] To build their career, Assistant Professors should be advisors of Ph.D. students. The biggest challenge that they face is obtaining the funding to support the student ($60,000 per year, for 3 to 4 years). Removing this financial burden by having the ERC pay the costs paves the way for talented Assistant Professors to build their careers faster. We supported 10 Assistant Professors from Mechanical and Industrial Engineering, of whom 5 did not attain tenure. The 5 Assistant Professors that were tenured include: Dawn Tilbury (NSF Assistant Director of Engineering), Jack Hu (VP Research, U. of Michigan, Member of the NAE), Jan Shi (Member of the NAE), and Amy Cohn (a full professor of IOE at UM).

As far as we know, usually Assistant Professors are not supported by the ERC grants, because their lack of experience risks the success of the ERC. However, we took this risk. You can see that although half of our Assistant Professors were not tenured, those who were tenured prove that our risk was well calculated.