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Generation Dynamics in Computer-Integrated Manufacturing Systems

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ABSTRACT

The application of generation dynamics, a methodology for technological forecasting, is widespread in computer-integrated manufacturing systems (CIMS). Experts' opinions about the past and future generations of technology are summarized for computer hardware, computer software, industrial robots, computer vision, computer-aided process planning, and the entire automated factory. The concept of generation dynamics has also been applied to products to be produced by CIMS and to the industrial environment of CIMS. Although experts in the same area do not completely agree with one another, their acceptance of experts' opinions on generation dynamics in other areas to be integrated by CIMS helps the forecasts to be mutually reinforcing and self-fulfilling. On the other hand, such relatively unquestioned acceptance, if and when experts' opinions in other areas become outdated, leads to assumption drag in forecasting.

Introduction

Revolutionary changes are taking place in manufacturing technology around the world in the form of computer-integrated manufacturing systems (CIMS), which integrate the islands of automation in product design, cell level production, and plant level production to improve industrial competitiveness. Massive implementations of advanced manufacturing technology in CIMS are commonly found in brand new, "greenfield" plants costing hundreds of millions of dollars, usually based on corporate strategic considerations rather than on conventional item-by-item short-term economic justifications [11]. However, even for well-established facilities, there is an increasing need for revolutionary, stepwise technological changes in manufacturing methods [7]. Flexibility as well as automation, to be achieved through CIMS, is considered necessary to optimize the chances of survival of manufacturing enterprises in the global environment of market uncertainty and product diversity [10]. Under these new strategy-oriented manufacturing conditions, it has been said that the factory over the next 10–15 years will experience the most rapid change in any of our major institutions, and that the "factory of the future" is finally becoming a reality [17].

Many major manufacturing companies, such as General Motors and General Electric, have formally established corporate programs under the name of the Factory of the Future

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(FOF), or its equivalent and variation. Multidisciplinary teams have been assembled from various departments in the company to work on these ambitious programs, with frequent and in-depth interactions with outside vendors, consultants, universities, and research institutes. Being in the midst of rapid and significant changes of manufacturing technology, the technical and managerial personnel in these communities are very future-oriented in their own conceptual development and mutual communications with one another. Technological forecasts and assessments in CIMS are a necessary and routine task in their multidisciplinary team work. "Technological reach," "next generation of technology," and, more specifically, "fifth-generation computers," are terms frequently used by engineers and managers in CIMS even if they do not have precise commonly accepted definitions for these terms. These terms have their origin in the concept of generation dynamics, a methodology of technological forecasting, which is not a rigorous discipline. The purpose of this paper is to summarize the state in which the concept of generation dynamics has been applied to the various areas related to CIMS, and the impact of their application on research management and technology planning in the field.

Concept and Approach

As mentioned above, technological forecasting is not an exact science. It is, however, possible to make informed judgments on the characteristics of future technology on the basis of the dynamics of technological changes, expert opinions, and certain assumptions of socioeconomic and technological trends [14]. The concept of generation dynamics is one of the methodologies with increasing use in technological forecasting [19]. The concept is based on the observation that modern technology has generally progressed in an orderly fashion, given a "surprise-free" global environment. The basic assumptions underlying such an environment are (Turn, 1974):

- No drastic and unexpected technological breakthroughs
- No major international conflicts
- No large-scale international depression or monetary catastrophe

It has been observed that in such an environment quantum improvements of technology take place between generations. The successive generations of technology in a given area tend to be equally spaced over time because it takes a certain time and effort, in industrial dynamics, to covert R&D into commercially available products, and because the leading companies in an industry need some time to write off their investment to reap reasonable profits.

The research approach that led to this paper was based on a combination of literature review, interview with experts, and extension of the author's previous work [2]. The interviews were conducted while the author was organizing a videotaped, multiple-speaker, graduate-level seminar course in CIMS at the University of Michigan. The interviewees included experts in the various areas of CIMS, located in universities, research institutes, and industrial companies, especially the team members with General Motors' Factory of the Future Program. Expert opinions in each area were obtained regarding technological generation dynamics in the experts' own area, and regarding the actual or potential impacts on their work by their understanding and assumptions of generation dynamics in other relevant technological areas. Their opinions were then compared and analyzed along with what was available in the literature.

Generation Dynamics of Various Areas within CIMS

The formal and informal application of the concept of generation dynamics has been found to be rather widespread in the various areas within CIMS. Experts in each area talk freely about how they have seen the major characteristics of technology changed over time from one generation to another in the past, and how they foresee the characteristics are to change in the future. Although there is no complete consensus among the experts in the same area, there seems to be a predominant view in each area and subarea.

As the computer is in the heart of CIMS, its generation dynamics is considered particularly interesting and important to both technical and managerial people in the factory of the future programs. The predominant view of computer generation dynamics is as follows [6]:

First generation computer—vacuum tubes, 1950s
Second generation computer—transistors, 1960s
Third generation computer—integrated circuits (IC), 1970s
Fourth generation computer—very large scale integration (VLSI), 1980s (present)
Fifth generation computer—artificial intelligence (AI), 1990s (?)

This view seems to apply to computers of all sizes (mainframe, mini, and micro), and to computers of both general and special characteristics (such as fault-tolerant computers). Although the fifth generation computer [15], characterized by artificial intelligence, is to be distinguished by its architecture and software, as well as hardware, the above schema is essentially oriented toward computer hardware.

In the area of computer software, the predominant view is focused on the generations of computer languages as follows [9]:

First generation language—machine languages, 1950s
Second generation language—assembly languages, 1960s
Third generation language—sophisticated procedural languages, 1970s
Fourth generation language—nonprocedural languages, 1980s
Fifth generation language—AI processing of natural languages, 1990s (?)

Admittedly, the timing of the generations is rather artificial since higher-level procedural languages like the early versions of COBOL and FORTRAN became widely used in the 1960s and may be considered creatures between the 2nd and 3rd generations. However, it is clear that basically the trend of computer languages is toward increasing user-friendliness. As exemplified by FOCUS, MARK V, RAMIS, IDEAL, etc., the fourth generation language (4GL) helps productivity improvement, end-user support, and decision support systems [13]. In the future, the fifth generation language will shift the emphasis further from machine efficiency to user efficiency.

During the past decade, robotics has become perhaps the most glamorous part of CIMS. Although there are different ways of describing the generation dynamics of industrial robots, the commonly cited one is as follows [5]:

First generation robots (1960s)—example: Unimation robots

- few degrees of freedom
- teach and playback facilities
- small memory

- relatively poor positioning accuracy
- relatively low weight handling capacity
- relatively low reliability

Second generation robots (1970s)—example: PUMA robots
- six degrees of freedom for any position and orientation within the work envelope
- computer control
- memory options ranging from 32 to 1024 program steps
- positioning accuracy repeatable to within 0.3 mm
- weight handling capability up to 150 kg
- high reliability—with no less than 400 hours mean time between failure (MTBF)

Third generation (1980s)—example: GM robots with vision
- over six degrees of freedom
- microprocessor sensing processing coupled with computer control
- large memory capability
- adaptive and flexible control
- multiple appendage hand-to-hand coordination
- self-diagnostic fault tracing

Perhaps the most important characteristic of the third generation industrial robots is the inclusion of sensors (as the future generations of robots will evolve with increasing levels of intelligence, which all require the use of sensors). Among the many kinds of sensors (force, tactile, etc)., the most important one is vision, which has found rapid and diverse applications in manufacturing systems over the past five years, with or without association with robotics. Even in its short history, the commercial machine vision system has developed a generation dynamics as follows [4]:

First generation machine vision (mid-1970s)
- binary vision
- detection and classification of images by blobs
- algorithm based on thresholds and histogramming
- two-dimensional statistical pattern recognition

Second generation machine vision (early 1980s)
- gray-level vision
- edge-based system
- algorithm based on smoothing and convolving images with edge detector
- dynamic two-dimensional scene analysis, with structural and syntactic pattern recognition

Third generation machine vision (mid-1980s and beyond)
- using two-dimensional images to derive three-dimensional information
- use of shape experts, including stereo, shading, texture, motion, occlusion, and shadows
- matching with three dimensional object models
- dynamic three-dimensional scene analysis

Note that multiple generations of machine vision systems may overlap or coexist as different vision applications may call for different degrees of technology sophistication [3].

The concept of generation dynamics applies to computer-aided design (CAD) as well as to computer-aided manufacturing (CAM) in CIMS. For example, in the area of computer-aided process planning (CAPP), the following progress has been made [8, 12].

First generation CAPP—variant approach, late 1970s
Second generation CAPP—semigenerative approach, early 1980s
Third generation CAPP—generative approach, late 1980s

The variant approach is to start with the process plan for a similar product (or part) and to vary the plan for adaptation to the given (or new) product. In contrast, the generative approach would generate a completely new process plan for the new product, without reference to any previously established process plan. The semigenerative approach is somewhere in between the variant and the generative approaches. Future generations of CAPP would use increasingly sophisticated artificial intelligence approaches to generate process plans automatically.

Generation Dynamics of Entire Manufacturing Systems and Their Environment

The concept of generation dynamics has been applied not only to the various areas within CIMS, but to the entire manufacturing systems and their environment as well. The past, present, and future entire factories may be considered as different generations of the automated factory as follows [16]:

First generation automated factory (1950s and 1960s)

- isolated single-task machines mixed with numerically controlled (NC) machines
- relay logic
- blueprint (paper) database
- no artificial intelligence (AI)

Second generation automated factory (1970s and 1980s)

- limited communications among multi-purpose machines
- programmable controllers (PC)
- geometric model in computer database
- AI in single machines (mainly for machine vision)

Third generation automated factory (1990s and 2000s)

- advanced computers and communications among flexible machines
- concurrent modeling of part geometry and process
- AI in cell-level production (machines to be told what task to do, but not how to do it)

Fourth generation of automated factory (beyond 2000s)

- intelligent factory to follow macro production command in natural language
- AI in plant-level production (cells and machines consult, negotiate, and decide how to carry out macro commands for manufacturing)

These images of the future automated factory often provide the basic guidelines for the research and development work in the factory of the future programs.

As indicated previously in the introductory section of this paper, a quantum jump in manufacturing technology in CIMS is often easier to justify strategically for a "greenfield" plant than for an existing plant. The consideration for a greenfield plant therefore often coincides with the design of a new generation of products to be produced by the new plant. On the other hand, CIMS technology is expensive. A company would not want to invest in CIMS technology for a product if the current generation of the product is to become obsolete soon. Thus, it is not surprising to find that the concept of generation dynamics has been applied to the products to be manufactured by CIMS. For example, automobile steering gear systems have several generations of evolution as follows:

First generation—mechanical rack and pinion (before 1975)
Second generation—mechanical/hydraulic, with some electronic controls (present)
Third generation—electronically oriented, no hydraulic pumps (beyond 1990)

The first pilot project of General Motors' FOF Program was to take a quantum jump in CIMS technology in the mid-1980s to produce parts for the current (2nd) generation of automobile steering gears, knowing that the 3rd generation steering gears are still some years away.

It is interesting to note that the concept of generation dynamics has been applied to the industrial environment of CIMS as well, with the result of encouraging corporate executives, strategic planners, as well as future-oriented technical people, to think in terms of eras, revolutions, transformations, as well as generations. For example, a major study of the automobile industry pointed to the following four transformations of the industry over its 60 years of history [20]:

First transformation (1920s)
  American mass production of automobiles
Second transformation (1940s)
  European diversification of car models
Third transformation (1960s)
  Japanese quality and just-in-time auto production
Fourth transformation (1980s)
  Global FMS and CIMS auto production

It is significant that three of the four transformations (all except the second one) are oriented toward production or manufacturing.

Observation and Impact

A couple of observations can be made on the basis of comparing experts' opinions on the generation dynamics of the various areas in CIMS. Within a single area, experts may disagree with the predominant view of the generation dynamics in that area. However, experts in one area tend not to challenge the predominant view of the generation dynamics in other areas.

The lack of a complete consensus among the experts in the same area has stemmed not so much from their forecasts of the future as from the diversity of their perspectives, which may be different but not necessarily incompatible. For example, four sets of generation dynamics have been reported for industrial robots [2]. In addition to the predominant view discussed previously, one set of generation dynamics focuses on the intelligence levels of robots, another set focuses on the mechanical subsystem, and still another focuses on the sensing subsystem. These four sets of generation dynamics are not incompatible, but are complementary to one another. Similarly, if one continued to focus on the hardware of computers, one might characterize the fifth generation computer by optical or hybrid processing [19], rather than by artificial intelligence, as discussed previously. The determining factors for a particular view to become predominant include the authority of the expert expressing the view, the frequency of the view being quoted or used by other experts in the same area and other areas, as well as the merit and the credibility of the view itself.

Since experts in one area may not have in-depth knowledge in another area, it is understandable why they tend not to challenge the predominant generation dynamics in the other area. In fact, they tend to accept the predominant generation dynamics in other areas in the planning for the R&D work in their own areas. This tendency has a significant impact on the development of CIMS, which requires assumptions about future technological changes in all interconnected areas in order that the technical work to be done by experts in many different areas can be integrated. For example, the development of the third generation computer-aided process planning (CAPP) will assume the availability of third generation robots, and the design of the next generation robots will assume the availability of the next generation machine vision, as described by the corresponding predominant generation dynamics. The net result of such mutual assumptions is the mutual reinforcement of technical development in the various areas of CIMS, thus helping the technological forecasts in all areas to become self-fulfilling prophecies. On the other hand, there is a danger of these mutual assumptions getting outdated if they remain unquestioned and unchallenged for too long. When some of these assumptions linger on beyond the point where they can be defended or remain plausible, they would lead to the phenomenon of "assumption drag" [1] that is frequently found in the practice of forecasting.[1]

References

1. Ascher, W., *Forecasting: An Appraisal for Policy-Makers and Planners.* Baltimore: Johns Hopkins University Press, 1978.
2. Chen, K., Chang, N., Technology Forecast of Space Robots to the Year 2000. *Technological Forecasting and Social Change* 26 (1984).
3. Chen, K., and Stafford, F. P. The Employment Effect of High Technology Industry—A Case Study in Machine Vision. *Report to the U.S. National Commission for Employment Policy* (1986).
4. Crowley, J. L. Machine Vision: Three Generations of Commercial Systems. CMU-RI-TR-84-1. Pittsburgh: Carnegie Mellon University, 1984.
5. Engelberger, J. F. Industrial Robots—Second Generation. *1972 Symposium on Robots.*
6. Feigenbaum, E. A., McCorduck, P. *The Fifth Generation: Artificial Intelligence and Japan's Computer Challenge to the World.* Reading, MA: Addison-Wesley, 1983.
7. Finlay, P. A., Updating the Technology of a Well-Established Industry. *Proceedings of the 3rd International Conference on Assembly Automation,* 1982.
8. Han, I. Computer Automated Process Planning. ITI/CRIM Seminar. Ann Arbor, MI: University of Michigan, September 26, 1985.
9. Harrison, W. L. *Computers and Information Processing: An Introduction.* West Publishing, 1985.
10. Hatvany, J. Optimizing the Chances of Survival. *Annals of the CIRP,* 33(1)(1984).

[1]The author is indebted to an anonymous reviewer for this observation about assumption drag.

11. Hundy, B. B. "Investment in New Technology and Corporate Strategy. Annals of the CIRP 33(1) (1984).
12. Kochhar, D. S. University of Michigan, private communications regarding the timing of the CAPP generations.
13. Martin, J., *Fourth Generation Languages*, Vol. I. Englewood Cliffs, NJ: Prentice-Hall, 1985.
14. Martino, J. *Technological Forecasting for Decisionmaking*. New York: American Elsevier, 1972.
15. Miller, R. K. *Fifth Generation Computers: A Report on Major International Research Projects and Cooperatives*. SEAI Technical Publishers, 1985.
16. Ruff, K.E. General Motors Corporation, private communications. The idea based on them is fitted to this paper, 1985.
17. Skinner, W. The Factory of the Future—Always in the Future?—A Management Viewpoint. In *Towards the Factory of the Future*. ASME PED-1, 1980.
18. Turn, R., *Computers in the 1980's*. New York: Columbia University Press, 1974.
19. Wise, K.D., Chen, K., Yokely, R. E. *Microcomputers: A Technology Forecast and Assessment to the Year 2000*. Wiley-Interscience, 1980.
20. Womack, J., Jones, D. The Fourth Transformation in Autos. *Technology Review* (October, 1984).