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R&D on Human- and Environment-conscious Manufacturing Systems

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1 Introduction

Japan's Third Science and Technology Basic Plan defines that a major policy challenge for the promotional strategy in the "MONODZUKURI Technology" (manufacturing technology) field is taking advantage of manufacturing capacity, a strength of Japan, and maximizing the added value created through a value chain extending even to service and information industries[1]. The plan proposes that Japan should solve its resources, environmental and population problems, to maintain international competitiveness, and to further develop the economy through these strategies. A value chain is an accumulation of added value created through R&D, manufacturing/assembly, sales, after-sales service, and recycling[2]. Assuming that sales and after-sales service activities are a process through which products (the result of production activities in the manufacturing sector) are utilized, advancing manufacturing systems can be an effective way of increasing the total added value of a chain. This suggests that addressing manufacturing systems as a strategy to promote MONODZUKURI technology is significant.

The Third Science and Technology Basic Plan sets six policy goals: "Quantum jump in knowledge, discovery, and creation," "Breakthroughs in advanced S&T," "Economic growth & environmental protection," "Innovator Japan," "Nation's good health over lifetime," and "The world's safest country"[3]. Among them, "Economic growth & environmental protection" and "Innovator Japan," which are based on the concept of "Maximizing national potential," emphasize that developing science and technology as a source of national strength is essential for overcoming constraints facing Japan, such as the aging and decreasing population, the declining birth rate, and global-warming/energy problems, and for creating a competitive nation capable of achieving sustainable growth even in fierce global competition[3]. In particular, the promotional strategy in the MONODZUKURI Technology field mentions "human-centered manufacturing practices" as a basic policy[1].

This article examines manufacturing systems that are human- and environment-conscious yet beneficial to economic growth, as a vision of what manufacturing systems should pursue. By showing concrete examples of the kind of manufacturing systems that Japan should pursue to simultaneously achieve environmental conservation and economic growth, the article identifies challenges to be addressed through future R&D for ensuring sustainable growth of the Japanese manufacturing sector's international competitiveness and building a human- and environment-conscious society.

2 Human and environmental issues listed in the MONODZUKURI Technology field

As Table 1 shows, the Third Science and Technology Basic Plan's promotional strategy for the MONODZUKURI Technology field selects 10 issues as major research themes, seven of which include keywords relating to humans or the environment[1]. In particular, many of such

Table 1 : Human- and environment-related keywords for production systems found in major research themes in the MONODZUKURI Technology field

Promotional strategies in the MONODZUKURI Technology field		Keywords
1. Situation recognition		
3. Strategic prioritized S&T (1) Science-based KASHIKA (dissemination and accessibility) technology for manufacturing that further advances Japanese-style MONODZUKURI technology		
2. Key R&D themes Promotion of MONODZUKURI technologies (areas) serving as a common infrastructure	(1) Enhancement of fundamental MONODZUKURI technologies based on IT	Japanese-style MONODZUKURI system technology Human-centered MONODZUKURI practices
	(2) Development of new measuring and analysis technologies and equipment and new precision processing technologies to meet the needs of MONODZUKURI	MONODZUKURI environment facilitating collaboration of workers Ensured safety of facilities and huge mechanical systems
	(3) Advancement of SMEs' fundamental MONODZUKURI technologies	
	(4) MONODZUKURI technologies contributing to building huge mechanical systems	Safety and security of society and people
3. Strategic prioritized S&T (2) MONODZUKURI process innovations to solve resources, environmental and population problems and serve as Japan's flagship		
2. Key R&D themes Promotion of MONODZUKURI technologies (areas) with the potential for innovations and breakthroughs	(5) MONODZUKURI technology to produce high value added materials to lead the world	
	(6) MONODZUKURI innovation using robots to cope with a depopulating society	Human-centered MONODZUKURI practices Collaboration with humans, safety, high-mix low-volume production, cell production support robots, work environment enabling women and elderly people to participate in MONODZUKURI MONODZUKURI labor shortage
	(7) MONODZUKURI innovation using biotechnology	Energy-saving, environment-friendly MONODZUKURI technology Environment-friendly, recycling-oriented society
	(8) Energy-saving MONODZUKURI processes	Energy-saving manufacturing technology Low-loss production processes based on design support systems that take life cycle into account
	(9) Resource-efficient, environment-conscious MONODZUKURI technology	Environment-conscious MONODZUKURI technology 3Rs (Reduce, Reuse, Recycle)
2. Key R&D theme Human resources development/exploitation and preservation and refinement of skills	(10) Promotion of the development and exploitation of human resources in MONODZUKURI	

keywords appear in Key R&D Themes (6) to (9) in "Manufacturing technology areas with the potential for innovations and breakthroughs" under Strategic Prioritized S&T (2), "Manufacturing process innovations to overcome resources, environmental and demographic constraints and serve as Japan's flagship." As already mentioned, the promotional strategy in the MONODZUKURI Technology field sets "human-centered manufacturing practices" as a basic policy. For environmental consciousness, the promotional strategy in the Environment field refers to the "3Rs" (Reduce, Reuse, Recycle) technology research area, details of which are shown in Table 2 as an excerpt[4].

Human- and environment-conscious manufacturing systems are also chosen as a key issue in the "Science and Technology Foresight Survey" series study, which has been performed with the aim of providing useful information for the discussion of prioritization in the Third Science and Technology Basic Plan. The

Table 2 : Major research themes in the 3R technology research area in the Environment field

Promotional strategies in the Environment field (excerpt)	
3R technology research area	
Key R&D themes (42) and (46) are strategic prioritized S&T in the 3R technology research area	
Key R&D themes Program 1: Technologies to design, evaluate and support production/consumption systems in a resource-recycling society	(42) System analysis/evaluation/design technologies to practice the 3Rs
	(43) Technologies to support construction of social systems to promote the 3Rs
	(44) Technologies for 3R-oriented product design, production, distribution and information management
Key R&D themes Program 2: Technologies to manage recycled resources by usefulness and harmfulness	(45) Technologies to support testing, evaluation and standards setting of recycled products
	(46) Technologies for useful material exploitation and hazardous material management to meet international 3R initiatives
Key R&D themes Program 3: Technologies for proper treatment/disposal of recycled/waste materials	(47) Technologies to utilize untapped resources according to regional conditions
	(48) Recycling technologies adaptable to social maturity and technological changes
	(49) Technologies for next-generation waste treatment and for ensuring safety and security

production field in the "Delphi Analysis"[5], a survey in this series, cites two areas: "production technology for products with strength which raises the value of the products" and "circulating type of manufacturing technology with a low environmental load." The five most cited issues among the survey respondents as needing government involvement for technical realization all fall within the "circulating type of manufacturing technology with a low environmental load" area. The "Scenario Analysis"[6] of the foresight study series also underscores the importance of human-conscious manufacturing systems. The report selects "super large-variety small-volume manufacturing systems" as a science and technology area making major social and economic contribution and potentially originating innovative knowledge over the next 10 to 30 years. This implies the need for meeting diverse customer requirements, or in other words, the need for human-conscious manufacturing systems capable of making products customized for individuals.

Another noteworthy movement relevant to the environment and industry is that the "White Paper on MONODZUKURI 2006"[7] declares that overcoming environmental constraints and ensuring business continuity (recovery from potential industrial accidents and natural disasters) for maintaining stable supply of products are two major challenges for the manufacturing sector. Similarly, the "Strategic Technology Roadmap" of the Ministry of Economy, Trade and Industry draws up a strategic technology map in the 3Rs field, defining the creation of a circulating type of economy and society as the goal[8]. Meanwhile, with widespread adoption of the ISO 14000 series standards, environmental issues constitute an essential part of today's corporate strategy for any companies who want to exercise their corporate social responsibility (CSR). In this area, Japan's legislation, which consists of a number of laws established under the umbrella of the Basic Environment Law, is designed to facilitate construction of resource-circulating systems in the phases of manufacturing/consumption, re-merchandising, and recycling.

3 Manufacturing systems in the MONODZUKURI technology field

3-1 Influence of the manufacturing sector on other sectors

Figure 1 shows the influence that an increase or decrease in the Japanese production sector's volume of domestic manufacture has on those of other industries, as described in the White Paper on MONODZUKURI 2006[7].

With this chart, the White Paper suggests that the production sector exerts a greater impact on the volumes of domestic manufacture of other industries than the service sector in a broad sense does. More specifically, by the weighted average among industries in the production sector, when an industry in the domestic sector increases its volume of domestic manufacture

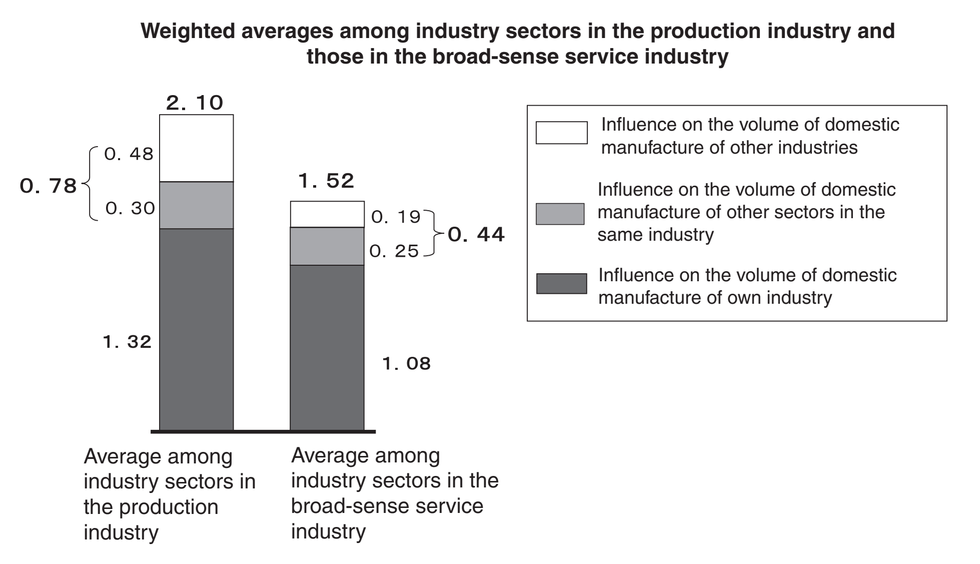

Figure 1 : Influence of a one-unit increase in a production industry's volume of domestic manufacture through its own manufacturing activity on the volume of domestic manufacture of all Japanese industries

The White Paper on MONODZUKURI 2006 estimates the influence that an increase or decrease by one unit in domestic manufacture in an industry has on the volume of domestic manufacture of all Japanese industries, including the own industry, with respect to 30 industries (including 14 production and 7 service industry sectors) identified through consolidation of 50 industries. The service industry in a broad sense refers to education, research, medical and health care, public service, corporate service, personal service, wholesale and retail, finance and insurance, real estate, and transport and communications. The White Paper uses the "Abbreviated Extended Inter-Industry Relations Table 2004" as a reference. Quoted from "White Paper on MONODZUKURI 2006"

through its own manufacturing activity by one unit, other production industries' volume from manufacturing activity grows by 0.30 unit, and non-production industries' by 0.48 unit. Combined with the effect on the volume of the own industry, the increase totals 2.10 units[7]. This is greater than the weighted average among industry sectors in the broad-sense service sector, 1.52. In short, the growth or decline in the added value amount of the production sector not only directly influences the volume of domestic manufacture of the specific industry, but also indirectly contributes to an increase or decrease in the added value amount of other manufacturing and non-manufacturing industries.

Manufacturing systems could contribute greatly to increasing the manufacturing sector's volume of domestic manufacture through its own production activity, because they are (A) mechanisms to make products in the production sector and (B) capable of managing total optimization of value chains.

3-2 Traditional frameworks of manufacturing systems

To explain efforts to date to advance manufacturing systems, this section describes the transition of manufacturing systems over years. Figure 2 shows changes in manufacturing methods and systems.

(1) Centralization and decentralization of manufacturing facilities[9,10]

Manufacturing facilities are divided into several functional units, such as processing, assembly and parts-transfer facilities. Computer integrated manufacturing (CIM) is a system that centrally controls these different units of facilities and integrates them with other plants' operations and corporate managerial information for total management. Large-scale CIM systems have already developed for practical use. Manufacturing systems are moving toward distributed management nowadays because centralized management is susceptible to changes in demand and equipment condition. The notion of giving each facility unit the capability of autonomous operation for distributed management is known as the autonomous, distributed, cooperative manufacturing system.

(2) Manufacturing adaptable to variety of product and manufacturing volume[9,10]

Manufacturing one or a few variations of

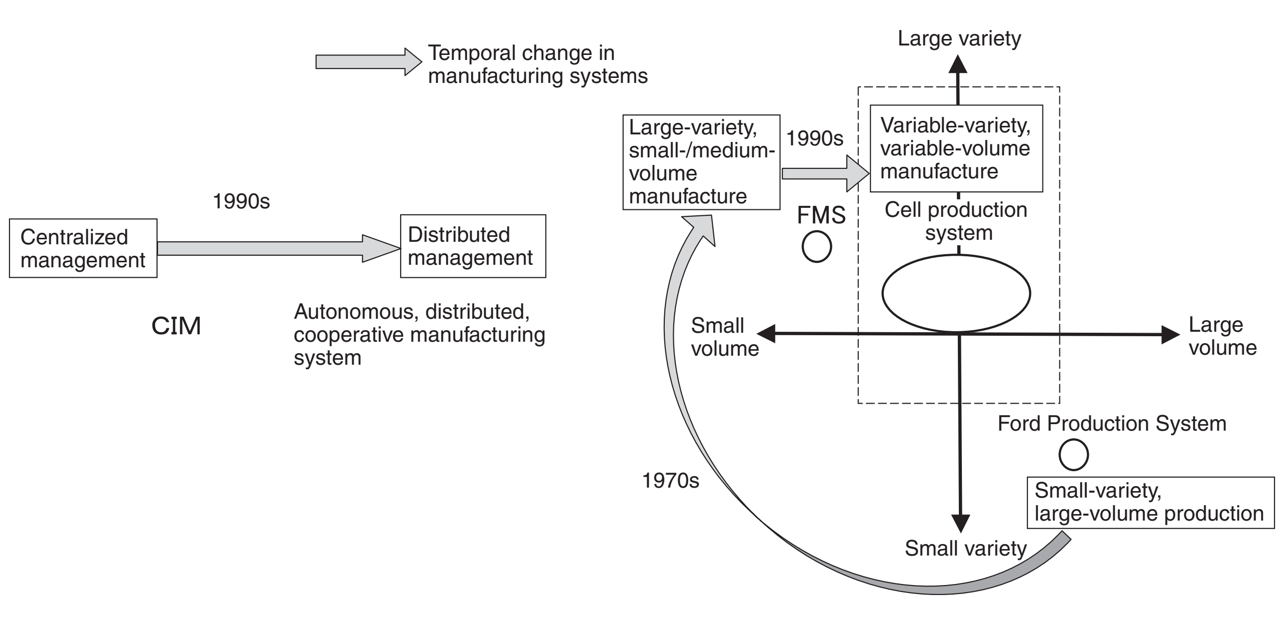

Figure 2 : Changes in manufacturing methods and systems

high quantity goods is called small variety large volume manufacturing, which is represented by the Ford Production System of the U.S. auto maker Ford Motor Company. As opposed to this, manufacturing of large variety and small to medium volume of products to meet a wide variety of needs and usage is typically enabled through a flexible manufacturing system (FMS). Nowadays companies pursue variable-variety, variable-volume production to adapt to dynamic and fast changes in the quantity and models being produced. A typical example is the cell production system.

However, all production methods and systems listed in Figure 2 coexist because centralized management and small variety, large-volume production are still effective for many products.

3-3 Human- and environment-oriented conception of manufacturing systems

Figure 3 depicts the structure of the "manufacturing system adapted to humans" and the "environment-conscious manufacturing system," which this article describes as human- and environment-oriented systems[9-12]. Major elements of the structure are explained below.

Manufacturing systems for production carry functions for premanufacturing processes, such as data creation to enable computer-aided machining and assembly, and those for manufacturing controls aimed at efficiently managing manufacturing lines as planned. Life cycle systems are a technology to optimize the cost of entire product life cycle, including operation and maintenance costs as well as production costs, based on time. Supply chain management (SCM) represents a technology to comprehensively manage all elements of procurement and sales activities conducted between the companies involved and optimize them by focusing on the flow of goods. This entails consideration of transport of products, since these interrelated companies are geographically dispersed. Specification requirements for a manufacturing system are growing in complexity year after year, as manufacturing systems continue to expand temporally and spatially.

Recent trends in R&D on manufacturing systems are summarized below[9-12].

(a) Capability to meet variable variable-variety and variable-volume
(b) Utilization of human capacity; Consideration of human characteristics
(c) Reduction of environmental load
(d) Quality improvement
(e) Satisfaction of diverse customer needs (short delivery time, ease of use, customization)
(f) Safe facilities

On the global level, a notable initiative is

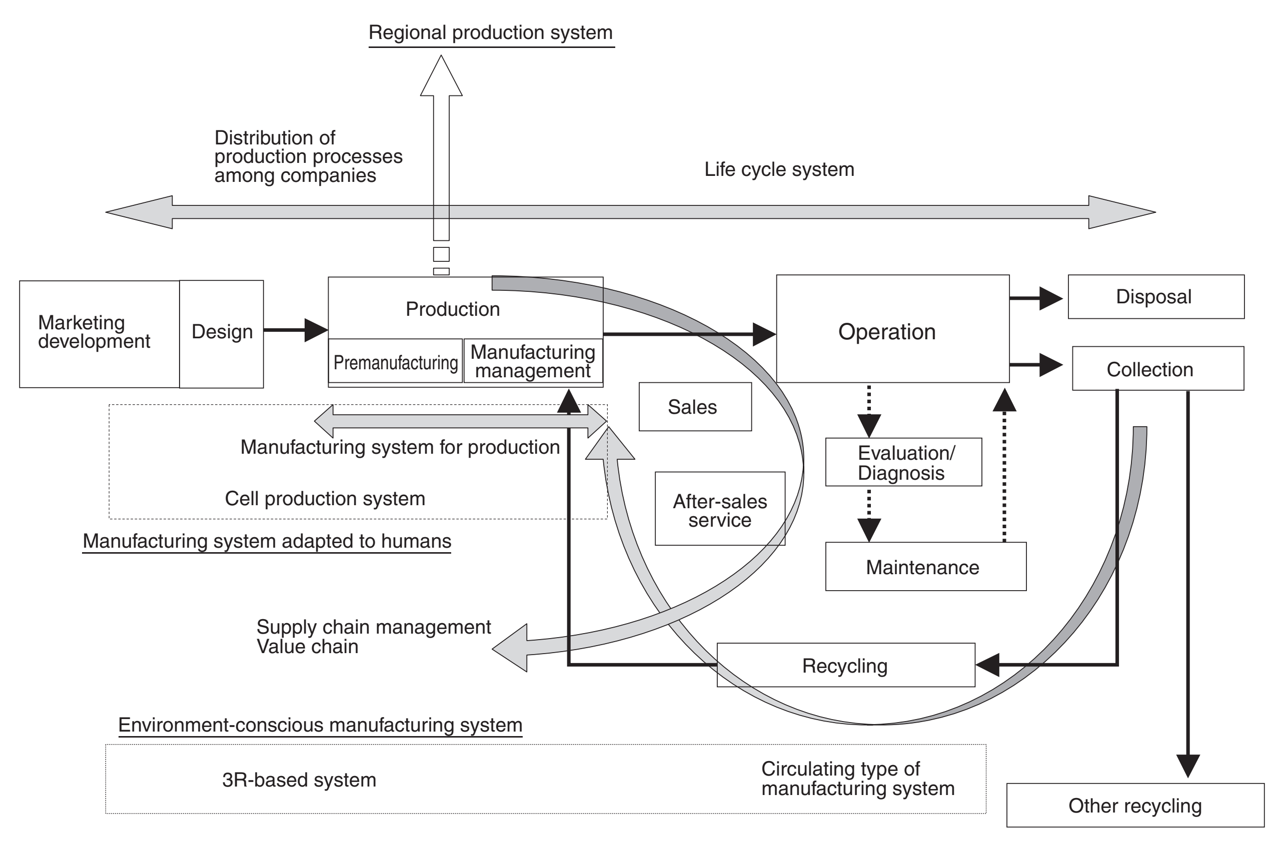

Figure 3 : Structure of human- and environment-oriented manufacturing systems

"Manufuture - a vision for 2020," a document compiled under the leadership of the European Commission in 2004. F. Jovane, a key member of the project, visited Japan in August 2006 and explained the strategic goals of Manufuture 2020 as follows[13]:

(a) Sustainable competitiveness of the European production sector
(b) Leadership in production technology
(c) Environment-friendly products and manufacture
(d) Europe's leadership in cultural, ethical, and social values

On the other hand, Japan has its own initiatives in this area. One research project, mainly consisting of researchers in economics and business administration, centers on a manufacturing system encompassing everything from socioeconomic structure to industrial relations to technology management strategy. Some other examples are seen among projects selected under the 21st Century COE Program (in social science field)[14]. The projects listed below deal with manufacturing systems from the same perspective as the first example.

(a) "Synthetic Research on Technology, Enterprise and Competitiveness," Doshisha University
(b) "Manufacturing Management Research Center," University of Tokyo

4 Directions of manufacturing systems

4-1 Manufacturing system adapted to humans

The promotional strategy for the MONODZUKURI Technology field cites "human-centered MONODZUKURI practices" as a basic policy, as mentioned earlier. An ideal manufacturing system pursued here is one that is economical yet friendly to humans. Although these two elements (human friendliness and economic efficiency) may seem incompatible, some research has demonstrated that human-centered manufacturing systems are more efficient than conventional ones.

(1) Expectations for manufacturing system adapted to humans

Two kinds of people are involved in a manufacturing system: workers, who operate the system, and users (buyers) of the products manufactured by them. From this perspective, requirements for a manufacturing system adapted to humans, or human-centered manufacturing systems, are defined as follows:

(A) From workers' point of view, a manufacturing system adapted to humans means one that they can control for their convenience. The opposite of this is a manufacturing system that workers cannot regulate by their own decision, such as a conveyer-based assembly line, in which operators need to complete assigned assembly tasks according to the movement of the conveyer belt.

(B) From the viewpoint of product users, a manufacturing system can be said to be adapted to humans if it enables users to buy or order products catering to their varied needs. This means being able to manufacture a variable (and many) kinds of products to meet even short-term changes in the product variety in demand, not simply providing a large variety of products over a long period. This model corresponds to variable-variety, variable-volume manufacturing listed in Figure 2. The opposite model would be large-, but fixed-, variety manufacturing, and small variety manufacturing that does not allow users to purchase products suitable for their needs and preferences whenever they want, or that give users little freedom of choice.

A manufacturing system that satisfies the above two requirements (A) and (B) while benefiting both manufacturing efficiency and quality is the cell production system, which is stated in Section 3-2 (2) (Figure 4)[9,10]. No other models that is of a practical level have been proposed so far that successfully incorporate economical yet human-centered design. Companies running cell production systems publicize on their web sites benefits brought by the new production model, such as improvements devised by workers and a sense of fulfillment workers have found[15].

(2) Structure of the cell production system and factors behind its effectiveness

Why can the cell production system meet the above two requirements and why is it proven effective in improving manufacturing efficiency and quality? These questions are answered below through an explanation of the structure of the cell production system and factors behind its effectiveness. Requirement (A), a manufacturing system designed to fit workers, is fulfilled through the factor described in 1), and Requirement (B), variable-variety, variable-volume manufacturing to cater to user needs, through 2) to 4).

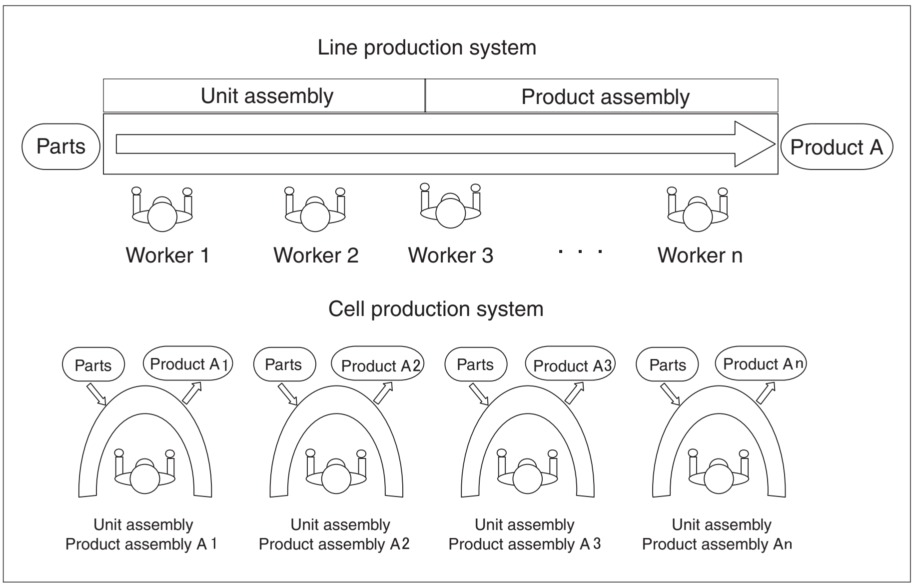

Figure 4 : Comparison of the line and cell production systems

1) In a cell production system, one to several workers constitute a work station called the cell, in which a product is completed by a single worker who undertakes the entire assembly process. The number of cells depends on the manufacturing quantity (Figure 4). A stronger sense of responsibility for each product encourages workerss to devise ideas to improve their work and equipment. By contrast, in a line production system, each worker acts like an incorporated function of a process.
2) In the cell production system, products are completed one at a time at each cell. The total volume of manufacture may be adjusted by increasing or reducing the number of cells assembling the same model. This contrasts with the line production system, in which manufacturing takes place on a lot basis and is therefore subject to overmanufacturing or waste. For example, in a production line with a lot size of 100, the volume can only be adjusted in increments of 100, which means that even when the required quantity is 120, 200 units must be made. On the other hand, no wasted manufacturing occurs in the cell production system because of its ability to regulate volume in increments of 1 unit. In addition, cells are so easy to install that manufacturers can quickly respond to changes in volume of manufacture by simply changing the number of cells.
3) As Figure 4 shows, the cell production system can have multiple exits for finished products, thereby enabling concurrent manufacturing of many varieties of products like A1, A2, . . . An.
4) Since the cell production system is self-contained, a worker's capacity affects only his or her own cell, and not other cells. In the line production system, which consists of a succession of processes each of which is assigned to a single person, the least efficient process determines the manufacturing efficiency of the entire system.

Items 2) to 4) describe advantages of the cell production system, in which products are assembled one at a time by one to a few operators. They enable variable-variety, variable-volume manufacturing and help improve economic efficiency.

Item 1) refers to workers' willingness and capability, and implies that workers tend to develop a sense of fulfillment and become more committed to the products they handle when multiple tasks are assigned. This often results in a higher motivation among worders and prompts them to propose ideas to improve work procedures, eventually contributing to improved manufacturing efficiency and quality. Research indicates that although a cell production system right after launch may not as efficient as conventional line production, the efficiency and quality improve with time to a point that outperforms line production.

(3) Basic structural problems, mechanisms and supplementary activities for cell production systems

The cell production system is a manufacturing model for making up products through an assembly process directed by humans, and in principle consists of work stations to which one to a few workers are assigned. However, this basic structure brings on several problems, to each of which remedies have been proposed in the form of improvement mechanisms or supplementary activities, as shown in Table 3.

(4) Examples of research aimed at expanding the applicability of cell production systems

(i) Research on unmanned cell manufacturing systems

Cell production systems are not suitable for products with too many man-hours for assembling by a single person or those incorporating heavy parts, as cited under (5) in Table 3. Solution to this problem is being sought from two different perspectives: (a) replacing human workers in cells with multi-function robots and (b) developing human-robot collaboration systems. These concepts, called robot cell production systems, pursue unmanned manufacturing systems for enabling variable-variety, variable-volume manufacturing and improving manufacturing reliability, rather than human-centered ones. However, it

Table 3 : Challenges for the basic structure of cell production systems, and mechanisms and supplementary activities to solve them

Challenges for the basic structure of cell production systems	Examples of mechanisms and supplementary activities to solve them
(1) Because of assignment of multiple tasks, it takes longer for workers to acquire skills than they would in a line production system, in which fewer tasks are assigned.	• Creating better training systems, manuals, work procedures before the launch of a cell production system
(2) Efficiency and quality vary depending on personal capability due to greater reliance on humans.	• Education on scientific work analysis methods • Product design for ensuring compliance with quality requirements at all cells
(3) The flow of goods is complex because of the concurrent operation of many production stations, each of which has a parts feeding port and an exit for products.	• Management to optimize the complex flow of goods, including parts supplied to cells and products being shipped (Utilization of SCM)
(4) Introducing expensive equipment is difficult because of a large number of cells, and facilities design requires consideration of operator safety and ease of use.	• Automated equipment equipped with a control panel with a user-friendly, error-resistant interface, to give control to the operator • Production facilities with advanced mechanisms for error prevention • User-friendly jigs to support efficient assembly
(5) Application to products with too many man-hours for assembly by a single person or those incorporating heavy parts is not feasible.	• Partial introduction of line production using conveyer belts • Assembly by a few operators through teamwork

is unlikely at least for the next five years that manufacturers will see practical robots that can completely substitute for human workers, with capabilities of performing tasks requiring carefully coordinated movement of both hands and meeting frequent change in the assembly procedure. On the other hand, there is a large need for research aimed at an ultimate unmanned manufacturing system, or a scheme known as low cost automation (LCA), to save human workers from human-unfriendly manufacturing processes, such as handling toxic chemicals and working in a high-temperature environment, that do not require variable-variety, variable-volume manufacturing. However, directions of such research are different from the ones that cell production systems essentially pursue.

(ii) Research on devices that extend human ability

This section primarily describes results of recent university research projects aimed at developing devices to extend human ability through human-centered structure, which is a major factor of the success of cell production systems. Since limitations of human ability are the major reason for inapplicability of current cell production systems, attention should be paid to research on (a) wearable devices that extend human ability and (b) devices that humans can control at their will. Figure 5 depicts the images of such research concepts.

An example of devices that humans can control at their will is a combination of a head-mounted display and a computer-aided assembly machine that superimposes computer graphics models of parts and equipment on the real images of them in a way the operator can refer to work procedures and relevant data. Through a user-friendly, error-resistant control panel, the worker would control this system at his or her will with ease and have it perform tasks. As a result, the system could reduce the worker's man-hours for assembly, thereby improving his or her work efficiency.

Example 1 of wearable devices that extend human ability in Figure 5 is an idea of using sensors that key skilled workers in a cell production system wear on their fingertips. These sensors, aimed at increasing work efficiency, will allow workers to identify the temperature of a part just by touching it with their fingertips. Electronic artificial skin using organic semiconductors (a multi-function sensor that can be worn on the hand)[16] in the same chart is a research project pursuing a flexible device consisting of numerous tactile sensors. This is an attempt to extend human sensing ability. A devise that is as easy to wear as work gloves yet has various sensing capabilities beyond humans would bring significant benefits.

Example 2 of wearable devices that extend human ability is a device that can be worn on the arm to extend human ability in accurate

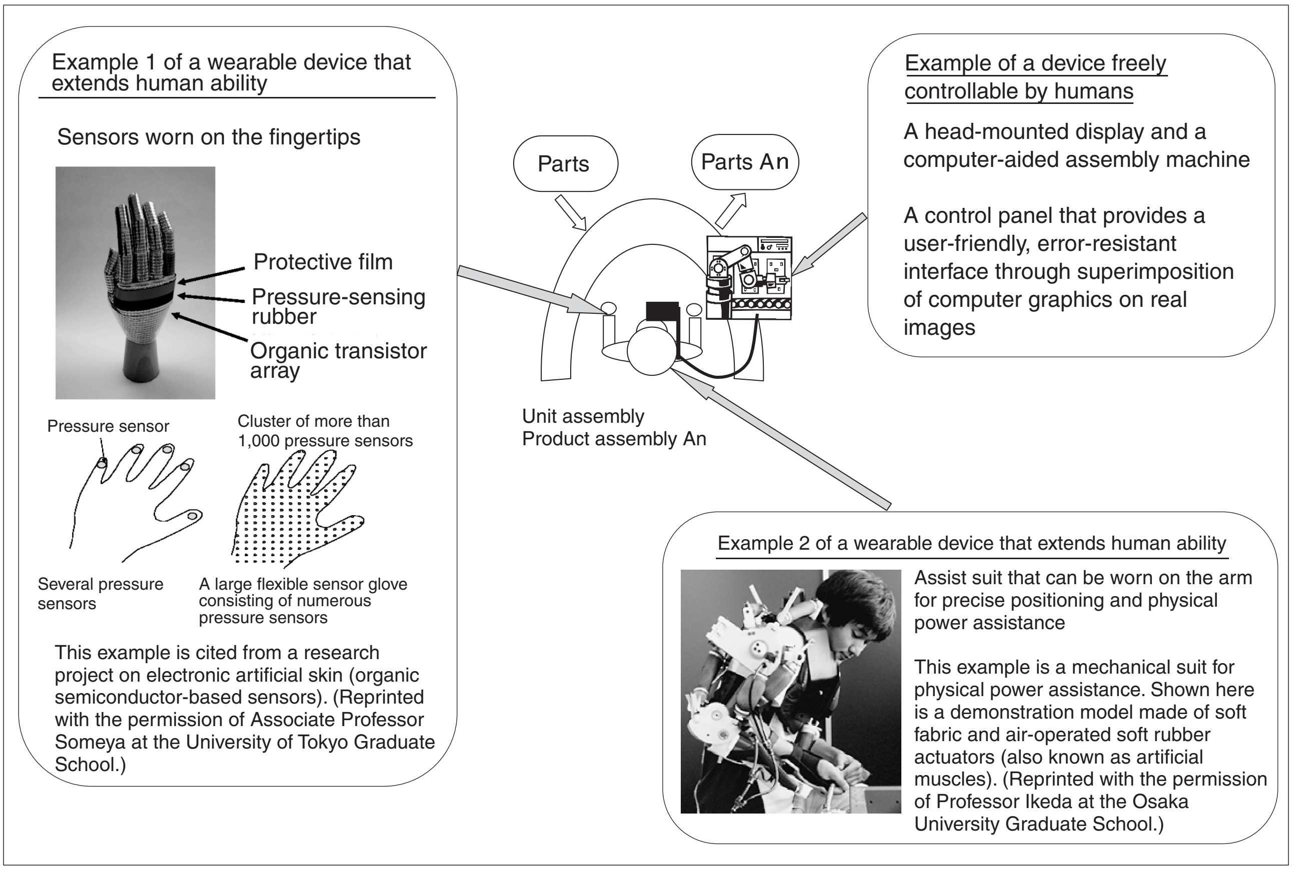

Figure 5 : Conceptual images of future directions of cell production system research

positioning as well as physical strength. Such research examples on power-assist tools[17] are attempts to enhance workers' handling ability. These devices would enable skilled cell production workers to (i) perform tasks more suitable for machines than humans, such as accurate positioning, and (ii) deal with heavy products, to which cell production systems are said to be difficult to utilize.

The most promising research direction with regard to manufacturing systems adapted to humans for the time being should be advancing cell production systems. Individuals engaged in cell production systems are skilled MONODZUKURI workers as well as technicians who may be able to advance their current cell production systems through improvements or proposal of improvement ideas. Cell production systems are characterized by high flexibility enabled by humans who control the entire process. This motivates workers and consequently makes manufacturing systems highly efficient. These facts suggest important two directions of research: human-centered wearable devices that extend human ability and devices that humans can control at their will. Research efforts should also be made for cell production systems applicable to a wider range of products, such as those incorporating heavy parts, and more adaptable to increasingly dynamic change in product variety and volume, driven by diversifying user needs.

4-2 Environment-conscious manufacturing systems

As mentioned earlier, the Third Science and Technology Basic Plan stresses simultaneous achievement of environmental conservation and economic growth as a policy goal. A wide range of activities are taking place in Japan, such as publication of reports on research trends in materials and waste treatment[18-20] and symposia on manufacturing systems seeking to bring benefits to both environmental conservation and economic growth[21].

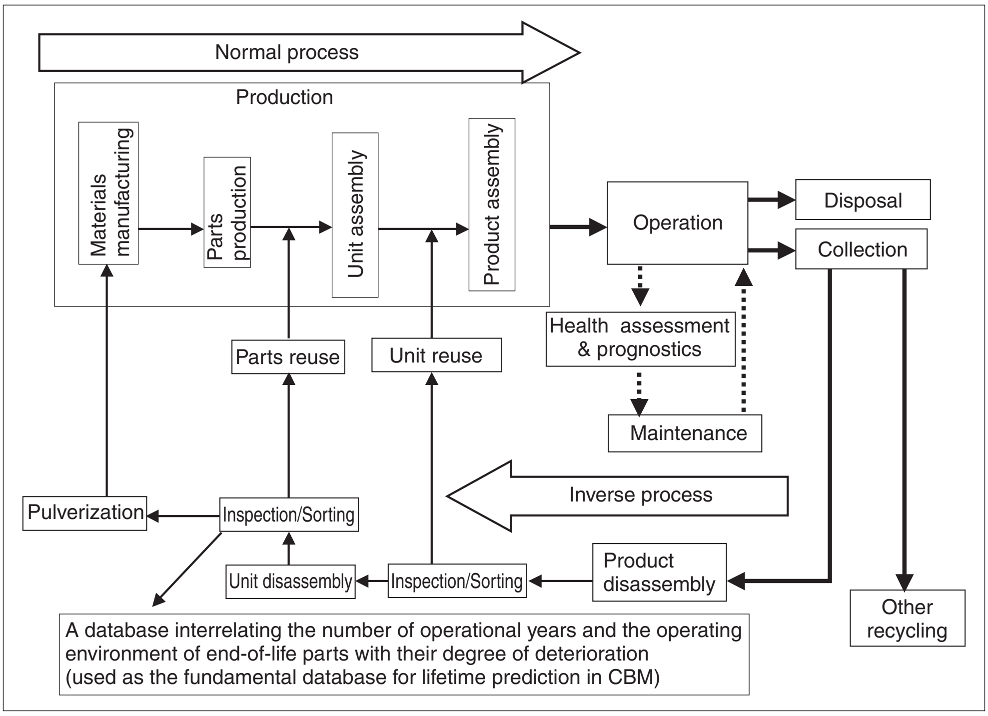

Figure 6 : Environment-conscious manufacturing system

(1) Structure of environment-conscious manufacturing systems

The ideal structure of an environment-conscious manufacturing system is shown in Figure 6. In general, the life cycle as a whole can shift to the circulating type by considering two mutually opposite processes: the process for making products, and the inverse process to deal with end-of-life products, which consists of collection, disassembly, inspection and sorting. Although it would be best if collected products' parts were reused, they are recycled as materials at the end of the inverse process. On the other hand, there is a notion of reducing unnecessary maintenance through parts replacement only as needed, which is known as condition-based maintenance (CBM). In CBM, parts are replaced according to their condition rather than at specific intervals. Many products are subject to periodical parts replacement throughout their operational lives to maintain performance. However, if the remaining lifetime of individual parts is predictable, they may be saved from unnecessary replacement, consequently reducing the environmental load. The cycle of "Operation - Health Assessment & Prognostics - Maintenance" displayed in Figure 6 represents CBM activities. In the health assessment & prognostics phase, maintenance decisions are made by estimating the remaining lifetime of parts based on a database interrelating the number of operational years and the operating environment of end-of-life parts with their degree of deterioration (the fundamental database for lifetime prediction).

(2) Challenges for circulating type of life cycles

An important consideration in product design is maintaining a balance between two factors that can be mutually contradictory: ease of assembly in the normal process and ease of disassembly in the inverse process. The design of a manufacturing system for the normal process must take the inverse process into account. Considerable uncertainty of parts supply through the inverse process makes supply chain management (SCM) complex. For total optimization of a manufacturing system, as in Figure 6, it is better if concerned companies are regionally concentrated. That is to say, a "regional production system" should be constructed to facilitate total production optimization, including coordination of companies engaged in the normal process and those specializing in the inverse process, through a regional concentration of

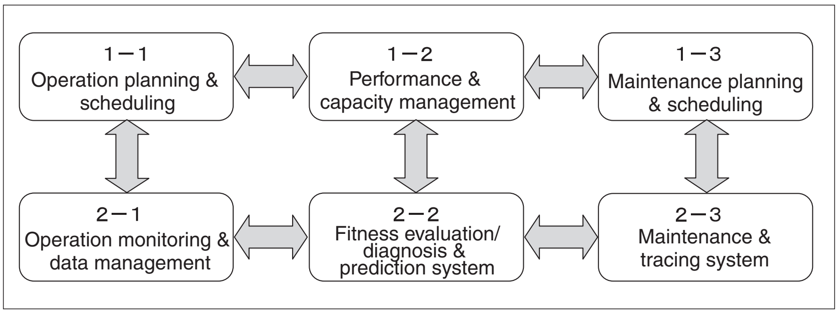

Figure 7 : The cycle of operation - health assessment & prognostics - maintenance

normal- and inverse-process industries. To enable circulating type of life cycles, research is needed in SCM and other technologies to optimize both assembly and disassembly processes across separate companies.

(3) Challenges for condition-based maintenance

Figure 7 represents the notion of condition-based maintenance (CBM). The cycle of "operation - health assessment & prognostics - maintenance" in Figure 6 refers to CBM activities.

Although theoretically estimating the remaining lifetime of a part from its condition is not easy, a database interrelating the number of operational years and the operating environment of end-of-life parts with their degree of deterioration based on analysis of those parts would contribute to fitness evaluation and diagnosis of parts in use. As shown in Figure 6, parts that have been determined not to be reusable as a result of "inspection/sorting" after "unit disassembly" in the inverse process may be utilized for creating such a database. The database would serve as the fundamental database for lifetime prediction. In Figure 7, the sequence "1-2 → 1-3 → 2-3 → 2-2" represents the maintenance cycle in CBM. The fundamental database for lifetime prediction would be useful in the process 2-2 "health assessment & prognostics." Accurate estimation of the remaining lifetime of parts is essential in this process. To improve prediction accuracy, research should be conducted on technology to measure the parts condition during "inspection/sorting" in the inverse process, on data models for the fundamental database for lifetime prediction, and on algorithms for such prediction. In summary, there is a need for research on CBM technologies that are effective for reducing waste generated from periodical replacement of parts before the end of useful life.

(4) Challenges for total optimization of environment-conscious manufacturing systems

Technologies to reduce the necessary amounts of resources and activity in specific sections of the manufacturing process can increase those amounts elsewhere in the process. For example, as far as the inverse process is concerned, an efficient recycling method is simply grinding collected products into small chips and reusing them as materials, rather than disassembling them at the expense of time and effort. However, this method will make it impossible to collect parts in a form useful as source data for CBM. This suggests that research only considering the rationality of a subsystem, such as disassembly, cannot produce enough effects of reducing total environmental loads.

A variety of studies are in progress to establish circulating type of life cycles through both normal and inverse processes[12,21]. Even local government are making efforts based on the results of national projects. In expectation of contribution to safe operations and preventing stoppage due to failures in the operation of products, CBM is studied as a technology that initiates a shift from periodical maintenance to maintenance on an as-needed basis through examination of the deterioration of parts. The structure of such a system is under discussion for standardization by ISO. Although circulating type of life cycles and CBM are currently two separate research themes, arguments in this article states that these two issues are closely related to each other, with respect to the total amounts of necessary resources and activity throughout a product's life cycle. Comprehensive research aimed at achieving an effect on minimizing those amounts in the entire life cycle is essential.

5 Conclusion

This article has presented examples of manufacturing systems that Japan should pursue in an attempt to achieve environmental conservation and economic growth at the same time. Here is a summary of what this article proposes as particularly notable directions of future R&D in Japan.

(1) Research on manufacturing systems on a partial or subsystem level leads to local solution of problems, possibly generating contradiction between solutions from a broad view. Although many key issues concerning manufacturing systems are identified by the government in its promotional strategy by field, optimization of the entire system should be taken into consideration in establishing concrete goals.

Breakthroughs in manufacturing systems are expected to contribute to increasing the added value of the production industry, which has a large influence on other industries. In particular, human- and environment-conscious manufacturing systems proposed in this article have a great potential for generating social and economic value. Japan should conduct R&D that takes into account the entire manufacturing system with the aim of raising the standard of Japanese industries across the board.

(2) There are two directions that human-conscious manufacturing systems should pursue: cell production systems based on human-centered framework that are (i) quickly adaptable to increasingly dynamic change in product variety and volume, driven by diversifying user needs, and (ii) applicable to a wider range of products, such as those incorporating heavy parts. Adopting cell production systems will motivate workers and can consequently improve manufacturing efficiency and quality through improvements to work procedures devised by motivated workers. To enable wider application, research efforts should be focused on the following issues:

(i) Wearable devices that extend human ability

(ii) Devices freely controllable by humans

(3) Environment-conscious manufacturing systems should be advanced toward a structure that combines a life cycle consisting of the normal and inverse processes with the fundamental database for lifetime prediction, which is useful for CBM. To this end, research on technologies to reduce the consumption of resources by enabling the reuse of parts should be promoted along with the following research issues:

(i) Optimizing technologies including SCM for both assembly and disassembly processes across separate companies involved in a circulating type of life cycle

(ii) CBM technologies based on the prediction of the remaining useful life of parts, which are effective for reducing waste generated from periodical replacement of still useful parts; especially technologies for improving the accuracy of such predictions

Through research in these areas, Japan should seek for manufacturing systems that can minimize the total amounts of necessary resources and activity throughout a product's life cycle.

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