A Model of Total Factor Productivity Built on Hayek's View of Knowledge: What Really Went Wrong with Socialist Planned Economies?

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Abstract

Because Hayek's view goes beyond the Walrasian framework, his descriptive arguments on socialist planned economies are prone to be misunderstood. This paper clarifies Hayek's arguments by using them as a basis to construct a model of total factor productivity. The model shows that productivity depends substantially on the intelligence of ordinary workers. The model indicates that the essential reason for the reduced productivity of a socialist economy is that, even though human beings are imperfect and do not know everything about the universe, they are able to utilize their intelligence to innovate. Decentralized market economies are far more productive than socialist economies because they intrinsically can fully utilize human beings' intelligence, but socialist planned economies cannot, in large part because of the imagined perfect central planning bureau that does not exist.

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1 INTRODUCTION

Most socialist planned economies (SPEs) collapsed or changed dramatically to largely decentralized economies in the late twentieth century. This fact clearly indicates that SPEs are far less productive and grow far more slowly than decentralized market economies (DMEs). In fact, the inferiority of the performance of SPEs as compared to DMEs has been so obvious that debate on the superiority between the two has almost disappeared in the twenty-first century. However, the reasons for the failure of SPEs have not been fully understood theoretically.

Debate over the two systems has a long history. The most well-known and important debate was the intense "socialist calculation" debate that took place during the interwar period in the 1920s and 1930s. Mises (1920) first asserted that SPEs are intrinsically unable to be as efficient as DMEs. Lange (1936, 1937, 1938) and Lerner (1944) responded to this assertion by showing an SPE model that is a mimic of a DME and is as efficient. Lange's model is strictly based on the equilibrium economics of Walras and appears perfectly correct from the Walrasian point of view. Therefore, many economists at the time considered Lange's model as the final answer to the question. However, Hayek (1937, 1945, 2002) countered that properly dealing with widely dispersed and privately owned information in an economy is the main difficulty in economic calculations and Lange's model does not mimic this important feature. Hayek argued that, in DMEs, entrepreneurs play important roles in fully utilizing widely dispersed and privately owned information. In contrast, in SPEs such a mechanism does not work because there is no incentive to do so and a central planning bureau (CPB) cannot substitute for entrepreneurs. Lange counter-argued that such an incentive is not necessary because it can be replaced with a rule. In Lange's model, a CPB need not necessarily determine everything. Instead, managers in dispersed plants are required to adjust the marginal cost in each plant according to a surplus or shortage by a predetermined simple rule.

If we limit our point of view to analyses within the Walrasian framework, the Lange-Lerner solution was considered to be a perfect answer; thus, before the 1970s, many mainstream economists accepted the defeat of Mises and Hayek in the socialist calculation debate as conventional wisdom (e.g., Lavoie, 1981). Stiglitz (1994) argued that, if the neoclassical model of economy were correct, the market socialism Lange showed would have been correct. Hayek's counter-arguments were viewed as focusing on trivial matters. For Lange, equilibrium in the Walrasian framework was the end goal, and he may have never understood the challenge posed by Mises and Hayek (Lavoie, 1981). However, the seriously malfunctioning economies of the USSR and other socialist countries increased people's awareness of the importance of Hayek's arguments. Many economists began to accept the possibility that all important aspects of an economy cannot be described only within the Walrasian framework. Therefore, even though Lange's SPE model may appear to show that SPEs can work as efficiently as DMEs from the Walrasian point of view, they may not actually work as well unless they can also mimic other important aspects of DMEs.

Currently, Hayek is widely viewed as the winner of the socialist calculation debate. However, this judgment seems to have been made mostly on the basis of historical fact—socialist states, such as the USSR, actually collapsed. Hayek, as a prominent opponent of SPEs, is admired mainly in reaction to this fact, but the admiration does not necessarily indicate that Hayek's arguments are fully understood and accepted theoretically. If anything, Hayek's arguments are prone to be misunderstood for two primary reasons: (1) they go beyond the Walrasian framework and (2) his papers are descriptive and do not use mathematical models and are thus viewed as ambiguous by many readers. The purpose of this paper is to make Hayek's arguments more straightforward by using them as a basis to construct a model of total factor productivity (TFP). With the model, we can quantitatively follow Hayek's ideas and thereby substantially reduce ambiguity, resulting in a clearer explanation of the collapse of SPEs.

The model is strongly based on Hayek's view of knowledge. He stressed that tacit and dispersed knowledge that is discovered during market processes is an essential element of DMEs. The knowledge is important because human beings are imperfect and cannot know everything about the universe. Because of human imperfections, many unexpected problems occur continuously during economic activities, and these occurrences are only locally known. Human beings are bestowed with intelligence, which they can use to generate innovations to fix unexpected problems. Hayek's view of knowledge includes all aspects of this widely dispersed information.

In particular, the model focuses on innovations generated locally by ordinary (average) workers. Innovations are usually presumed to be created by researchers and other highly educated or trained employees, and this bounded nature of innovation has been explicitly or implicitly assumed in most economic analyses. However, conceptually, innovations are not necessarily created only by researchers and similarly highly trained employees. At its core, innovation is the act of introducing something new or it is something that has been newly introduced; the concept does not exclude things or processes created by ordinary workers. The question is whether workers who are not well educated or highly trained can innovate, that is, create something new. The answer to that question is yes, even if most of the innovations are minor, because workers are human, possess intelligence, and therefore have the ability to create.

The model shows that the economy's overall productivity depends substantially on ordinary worker's innovations, i.e., their intelligence. Without innovations, productivity remains very low. In a DME, workers' innovations are fully utilized because they benefit both entrepreneurs and workers, and thereby entrepreneurs fully exploit the opportunity that workers' innovations provide. On the other hand, in an SPE, productivity remains at far lower levels than those found in a DME because the CPB cannot sufficiently obtain and process information on the intellectual activities of tens of millions of workers and managers. A pure SPE is therefore intrinsically far less productive than a DME.

My paper is organized as follows. In Section 2, Hayek's view of knowledge is summarized and a model is constructed on the basis of that view in Section 3. The productivity of SPEs and DMEs is compared using the model in Section 4. Scientific innovations in SPEs are specifically examined in Section 5, and some related topics, such as China's socialist market economy, are discussed in Section 6. Finally, I offer concluding remarks in Section 7.

2 HAYEK'S VIEW OF KNOWLEDGE

Although knowledge is often regarded specifically as scientific knowledge, Hayek emphasized knowledge of the particular circumstances of time and place. This type of knowledge is important because economic environments and conditions constantly change. Hayek argued that the nature of "changing every moment" is at the core of DME.

> [T]oday it is almost heresy to suggest that scientific knowledge is not the sum of all knowledge. But a little reflection will show that there is beyond question a body of very important but unorganized knowledge which cannot possibly be called scientific in the sense of knowledge of general rules: the knowledge of the particular circumstances of time and place. It is with respect to this that practically every individual has some advantage over all others in that he possesses unique information of which beneficial use might be made, but of which use can be made only if the decisions depending on it are left to him or are made with his active cooperation. (Hayek, 1945)

Hayek went on to add, "[T]he knowledge of which I am speaking consists to a great extent of the ability to detect certain conditions—an ability that individuals can use effectively only when the market tells them what kinds of goods and services are demanded, and how urgently" (Hayek, 2002). For Hayek, the role of markets and prices is not only the allocation of resources but also the discovery of knowledge under constantly changing circumstances. Dispersed tacit knowledge about particular circumstances possessed by a person at a particular point in time and space is discovered during the market process by entrepreneurs who are seeking profit opportunities. Although the concept of equilibrium presupposes that the relevant facts have been discovered and that the process of competition has thus come to an end, competition actually does not end at any moment in an always changing economy because competition is systematically a procedure for discovering facts.

Note that this concept of knowledge is different from that of private information used in the economics of information. An important feature of knowledge from Hayek's point of view is that it can be tacit (Hayek, 1967), and a person may unconsciously possess knowledge but may become aware of the knowledge during the market process. Even though a person does not know *ex ante* the knowledge as given information, the knowledge may become known publicly through the market mechanism *ex post*. On the other hand, private information is given to a person *ex ante* and is not known to the others even *ex post*. Contract theory generally assumes that information is given in advance and the principal and the agent make a contract considering given information, whereas Hayek considered the phenomena of change and discovery during the market process. That is, the economics of information is still situated within the Walrasian framework, but Hayek's arguments go beyond it so the contractual problems that the economics of information and contract theory deal with are basically irrelevant in this context.

The importance of the knowledge originates in the imperfect nature of human beings. As a result, many unexpected problems occur during daily economic activities in widely dispersed locations. Such unexpected problems substantially hinder economic activities, but human beings are not completely powerless to address these problems because they are bestowed with intelligence. With intelligence, human beings can fix unexpected problems through innovation. Notice that the knowledge of unexpected problems and the corresponding innovations are inevitably unknown *ex ante*.

Hayek argued that economists who consent to Lange's model ignore the imperfections in knowledge and in the dispersal of information: "[T]he knowledge of the circumstances of which we must make use never exists in concentrated or integrated form, but solely as the dispersed bits of incomplete and frequently contradictory knowledge which all the separate individuals possess" (Hayek, 1945). From Hayek's point of view, the market is a disequilibrium non-Paretian process that is completely different from the one depicted in the Walrasian framework, which focuses on equilibrium with static information. For Hayek, the disequilibria that originate in dispersed new discoveries are one of the most important elements that make the market indispensable. These disequilibria indicate new opportunities for profit-seeking entrepreneurs, through which the economy is vitalized. Hayek called this market process "spontaneous order."

As a consequence of his deliberation on the process of spontaneous order, Hayek concluded that knowledge of the particular circumstances of time and place possessed by the "man on the spot" can only be utilized in decentralized markets and that markets are superior to socialist planning not because they can achieve more efficient resource allocation in the Walrasian sense but because they better discover and utilize dispersed personal knowledge.

3 WORKERS' INNOVATIONS

To better understand Hayek's arguments on knowledge, I first examined the mechanism of knowledge generation. To begin with, I examined how an unexpected problem is fixed through workers' innovations at dispersed production sites. Here, I use Harashima's (2009) TFP model that well describes the mechanism of innovation generation at dispersed production sites.

3.1 Innovations generated by ordinary workers

3.1.1 Non-accumulative innovation

3.1.1.1 Innovations need not be intrinsically accumulative

Innovations are usually considered to be intrinsically accumulative, and TFP reflects the total sum of innovations that have been created and accumulated in the long history of human beings. However, accumulativeness is not a necessary condition for innovation because, as discussed in the introduction, its core meaning is the act of introducing something new or the thing itself that has been newly introduced. Luecke and Katz (2003) argue that innovation is generally understood as the introduction of a new thing or method and the embodiment, combination, or synthesis of knowledge in original, relevant, valued new products, processes, or services. The essence of innovation is therefore not accumulativeness but newness.

Nevertheless, non-accumulative innovations have drawn little or no attention in economics because innovations that are not accumulated have been regarded as being without value from an economic point of view. Accumulated innovations are often thought of as knowledge or technology, and they are usually regarded as equivalent to TFP. An innovation that is not accumulated is not included as knowledge, technology, or TFP because these must be commonly accessible and non-accumulative innovations are not. From this perspective, non-accumulated innovations are considered to have no effect on production and therefore be meaningless. The neglect of non-accumulative innovation may also be partially attributed to the belief that innovations must be accumulated because they have the innate nature of spillover (i.e., transfer), which implies accumulation. If an innovation makes someone better off, rational people have incentive to obtain and utilize it; thus, the innovation spills over. To spill over, the innovation must be recorded and transferrable in advance, that is, accumulated as a common piece of knowledge or technology. Conversely, innovations must be accumulated if they are consistent with the incentives of rational people.

However, the above rationales do not necessarily hold, for the following reason. A non-accumulative innovation is without value to people who did not create it, and the above rationales are convincing if only those people are considered. There is, however, no *a priori* reason that a non-accumulative innovation is valueless to the person who created it because that person can utilize it personally for production even if others cannot. Therefore, even if an innovation is not accumulated and does not become common knowledge, it still can contribute to production. A non-accumulative innovation may even be an important production element for the person who created it. In addition, if the costs to acquire an innovation created by other persons are higher than its benefits, the innovation will not spill over. Therefore, the concept that some innovations do not spill over and are not accumulated is not inconsistent with rational people’s incentives for using innovations. Clearly the accumulativeness of innovation is not a simple issue and requires more careful consideration.

3.1.1.2 Innovations that are not accumulated

Innovations will be used personally even if they are not recognized and recorded. In addition, some innovations may be deliberately kept personal. Hence, an innovation will not be accumulated if nobody is aware of the innovation’s novelty, nobody records or reports the innovation, or the person who created the innovation keeps it secret. The above conditions will be satisfied in the following situations. An innovation will not be recognized or recorded if the innovation is minor or if the innovation can be applied only to an unrepeatable incident. In addition, an incentive to keep an innovation secret will be strong if the person who creates the innovation cannot gain enough benefits by making it public. Thus an innovation will not be recorded if the costs of making the innovation public are higher than its expected benefits.

3.1.1.2.1 Minor innovations

A person who creates an innovation may be unaware of having created it if its contribution to improving productivity is minor. The person may also notice the increased productivity but not seek to identify the reason for the improvement because such an investigation may seem too costly. Finally, even if the mechanism of the innovation is noticed and specified, the person who created it may not record it if it is deemed to be minor. It is therefore clearly possible that minor innovations are not noticed, identified, or recorded.

Even if an innovation is unnoticed or unrecorded, it still can be used for production by the person who created it, whether consciously or unconsciously, while the person continues doing that job. Unnoticed innovations will vanish when that person quits doing the job. If innovations are recognized but unrecorded, it is possible that at least some of them could be handed down to other workers. Because these are isolated and "personal" occurrences within a small closed group, they would not constitute a piece of accumulated knowledge common to all human beings.

3.1.1.2.2 Innovations for unrepeatable incidents

Even if an innovation is not minor, it will not be recorded if it can be applied only to an unrepeatable situation. For example, a negotiation between a seller and a buyer will be basically unrepeatable. Similar negotiations may occur, but an identical one will not. There are also incidents that occur, for example, only on a specific machine installed at a particular location; these incidents are never reproduced at other machines installed at other locations. This type of isolated and non-reproducible incident can be interpreted as unrepeatable in a broad sense. In addition to these spatially unrepeatable incidents, each machine has unique characteristics even if it was designed to be exactly the same as other machines. There will not be sufficient incentive to record or widely disseminate an innovation that can be applied only to an unrepeatable situation or to a machine with unique characteristics.

3.1.1.2.3 Costs of disseminating and acquiring information

There will be a strong incentive to keep an innovation secret if the innovation spills over freely without compensation to the innovator. However, even if a patent could be taken out to obtain appropriate compensation, the incentive to keep the innovation secret will still be strong if the cost of dissemination exceeds expected revenues. If an innovation was created for a minor incident, benefits gained from the innovation will usually be smaller than the cost of dissemination, and the incentive to keep the innovation personal will be strong. The costs for making an innovation public can be classified into two types: dissemination costs and acquisition costs. Dissemination costs are the costs paid to make an innovation public and to disseminate it, for example, patent application fees, advertising costs, marketing costs, and similar expenditures. Acquisition costs are the costs paid to acquire and utilize an innovation that some other person created, for example, search costs, transportation costs, and training costs. Patent royalties are included in acquisition costs only if the market value of the innovation exceeds the royalty plus other acquisition costs. Generally, dissemination costs are likely to be larger than acquisition costs, excluding patent royalties.

Let δ indicate dissemination costs, η indicate acquisition costs, and π indicate the market value of an innovation. As argued above, in general $\delta > \eta$ if $\delta > \pi$; therefore innovations are categorized into the following three ranges depending on the relative value of π compared with those of δ and η (see Figure 1):

Range I: $\pi \geq \eta \geq \delta$ or $\pi \geq \delta \geq \eta$; patented accumulative innovations

Range II: $\delta > \pi \geq \eta$; uncompensated spillovers of accumulative innovations

Range III: $\delta > \eta > \pi$; non-accumulative innovations

If the market value of an innovation exceeds its dissemination and acquisition costs, the patent of the innovation will be sold and disseminated widely (Range I). If the market value of an innovation does not exceed its dissemination costs but exceeds its acquisition costs, the innovation will disseminate widely without compensation (i.e., uncompensated spillover; Range II). If the market value of an innovation does not exceed either cost, the innovation will not be disseminated and will be kept personal (i.e., non-accumulative innovation; Range III). Because it is highly likely that the number of minor innovations is far larger than the number of innovations that have high market values, the shape of innovation distribution slopes downward and to the right (Figure 1), and the distribution will have a long tail. This shape can be approximated simply by an exponential or Pareto distribution, but it is not necessary to assume a specific functional form of distribution. The important point is not the specific functional form of the distribution but its properties—if $\delta > \eta > \pi$, then non-accumulative innovations exist and there will be far more of them than of accumulative innovations.

3.1.2 The origin of non-accumulative innovation

It seems clear that non-accumulative innovations exist, but who creates them? Researchers can certainly create them, but so can ordinary workers. Usually, workers are implicitly assumed to do only what they are ordered to do and nothing else. Workers in this sense can be substituted for capital. If the cost of using capital is lower than that of using workers, capital inputs will be chosen rather than labor inputs. Generally, such robot-like workers have been assumed as the labor input in typical production functions. Of course, workers are not robots. They are human beings that are fundamentally different from machines—only humans can fix unexpected problems by creating innovations.

3.1.2.1 Unexpected problems require innovation

Actions taken to deal with expected incidents are determined by calculating the solutions to optimization problems that are built based on models constructed in advance. These calculations can be implemented by machines given a specific objective function, structural equations, parameter values, and necessary environmental information. However, this is not true if actions taken to deal with unexpected problems are required, because the models constructed in advance are guaranteed to be useful only for expected incidents, and they are not necessarily guaranteed to be applicable to unexpected incidents. When an unexpected problem occurs, workers in charge of the production first have to grasp the situation and then prioritize their actions. During these actions, the workers conduct two types of important intellectual activities: (1) discover unknown mechanisms that prevail in the surrounding environment and (2) invent new ways to manage the environment. That the problem is unexpected indicates that correct mechanisms for this particular situation are not known and need to be discovered, and on the basis of the newly discovered mechanisms, the structural equations and parameters in the model used for the plan of action should be revised. The revised model may indicate that there is no solution to resume efficient production, and new ways of managing the environment should be invented. Discovery and invention commonly involve the creation of something new, that is, innovation.

Machines deal with programmed tasks quite well, often much better than human beings. Conversely, machines cannot deal with non-programmed tasks. The performance of machines declines and often they stop working if unexpected problems occur because the machines do not have a program to deal with unexpected problems. When encountering unexpected problems, machines will immediately reach a dead end. They cannot solve unexpected problems by simply applying their pre-programmed optimization algorithms, and they cannot rewrite these algorithms to make them applicable to unexpected incidents. The revision or creation of models in the face of unexpected incidents can be implemented only by human beings.

3.1.2.2 Workers' innovations to fix unexpected minor problems

Is it either necessary or expected to utilize workers' innovations for production? If workers are assumed to be robot-like beings, their abilities to solve unexpected problems will not be considered as part of production. However, it would be irrational for firms not to utilize workers' innovative abilities if the firms know that workers possess these abilities. An ordinary worker's ability to solve unexpected problems may be lower than that of educated and trained researchers, but the abilities of the former should be utilized fully for a firm to be rational. If anything, the workers' abilities to fix unexpected problems appear indispensable in production processes because many minor but unforeseeable incidents actually occur. It would be quite inefficient if a team of specialized highly educated and trained employees dealt with all unexpected incidents, no matter how minor, and workers had to wait for the team to arrive at the locations where a minor unexpected incident happened. If, however, an unexpected but minor problem is fixed by a worker at the location where the problem occurred, production can proceed more efficiently and smoothly. The well-known "Kaizen" method in Japanese manufacturing companies may be a way to more completely exploit such opportunities (e.g., Lee et al., 1999). Besides innovations by suppliers, "user innovation" by consumers and end users has drawn attention recently (e.g., Baldwin et al., 2006). It is quite reasonable and rational for firms to fully exploit any opportunity to improve productivity whether its source is an innovation created by a researcher, ordinary worker, or user.

Finally, a worker's ability to fix unexpected problems may seem to be part of the set of the worker's learned skills or techniques, but that ability is fundamentally different from learned skills or techniques because learning skills and techniques and creating skills and techniques are completely different activities.

3.1.3 Imperfections make workers' innovations indispensable

Although it is rational for employers to fully exploit workers' innovations, in this section, I explain why workers' innovations are truly an indispensable element in production.

3.1.3.1 Imperfect accumulated innovations

The current state of accumulated innovations is far from perfect, and, moreover, it always will be. Human beings will never know everything about the universe. Although we may be able to fully utilize known information, we still face many unexpected problems because the knowledge and technology we currently possess is imperfect. If accumulated innovations were perfect, machines that embody them would always work well in any situation. However, the accumulated innovations are not perfect, and thus machines malfunction occasionally or face other unexpected incidents. As stated previously, it is very efficient if workers' innovations are utilized to fix these minor but unexpected troubles. Imperfection of accumulated innovations therefore necessitates workers' innovations.

3.1.3.2 Incomplete information caused by the division of labor

Labor input has the property of decreasing marginal product, which is usually explained by congestion or redundancy. However, this explanation is not necessarily convincing. The inefficiency caused by congestion or redundancy can be removed by division of labor. If labor is sufficiently divided, there will be no congestion or redundancy, and the labor input will not exhibit decreasing marginal product. This suggests that division of labor cannot remove all inefficiencies with regard to labor input. With division of labor, each worker experiences only a fraction of the whole production process. These divided and isolated workers can access only a fraction of information on the whole production process. It is also difficult for a worker to know information that many other workers at different production sites accessed. Because all of the labor inputs are correlated owing to division of labor, this feature of fragmented information is especially problematic when workers engage in intellectual activities. Correlation of the entire labor input indicates that all pieces of information on the whole production process need to be completely known to each worker to enable correct decision making. However, only a portion of the information on the whole production process is available to each worker; that is, each individual worker has incomplete information. When an unexpected problem occurs, workers with fragmented and incomplete information will make different, usually worse, decisions than those with complete information. As a result, overall productivity decreases.

For example, a CEO of a large company may know the overall plan of production but not the local and minor individual incidents that happen at each production site each day. In contrast, each worker at each production site may know little of the overall plan but a great deal about local and minor individual incidents that occur for each specific task each worker engages in at each production site. To be most efficient, even if many unexpected incidents happen, all of the workers and the CEO need to know all of the information on the entire process because all of the labor inputs are correlated owing to division of labor. However, it is nearly impossible for each worker to access all of the experiences of every other worker. Division of labor therefore leads to information fragmentation and obstructs any person from knowing all the information about the entire production process.

Each worker therefore must use incomplete information when encountering unexpected problems. Conjecturing the full detailed structure of the whole production process is an intellectual activity to discover unknown mechanisms. If a worker can discover more correct mechanisms even in the absence of complete information, the inefficiency is mitigated. Because inefficiency is inevitably generated by incomplete information resulting from division of labor, workers' innovations are inevitably needed to mitigate inefficiency. However, completely mitigating the inefficiency will be impossible, and decisions based on less information will deviate from those made with full information. Sometimes actions that are relatively less urgent or important will be given priority, and efficiency will decline. As the division of labor increases, workers are less able to correctly estimate the full structure of the whole production process and less able to correctly prioritize actions to solve unexpected problems.

Division of labor cannot simultaneously solve inefficiency caused by congestion or redundancy and that caused by fragmented and incomplete information. Although a greater division of labor removes the former, it generates the latter. Inefficiency resulting from congestion and redundancy is probably much more serious than that caused by information fragmentation, and labor is divided almost completely despite the fact that information fragmentation harms productivity.

3.1.3.3 Indispensable and economically important workers' innovation

Even if workers can innovate to fix unexpected minor troubles, the question remains whether these innovations are important economically. In general, most non-accumulative innovations are minor, which suggests that they may not be economically important. However, as discussed in Section 3.1.1, there will be far more minor innovations than major innovations. There are also usually far more ordinary workers than researchers and other highly trained or educated employees. In addition, the distributions of innovations for researchers and other highly trained employees and for ordinary workers are certainly different. Ordinary workers are likely to have a limited contribution to accumulative innovations (i.e., Ranges I and II in Figure 1) as compared to that of researchers and other highly trained employees, but the former will have a much larger contribution to non-accumulative innovations (Range III). As previously discussed, non-accumulative innovations are indispensable for production at each production site because of imperfect accumulative innovations and fragmented and incomplete information. Without worker-created non-accumulative innovations, the efficiency of production will decline considerably. This indispensability indicates that workers' innovations are economically important. The economic importance of workers' innovations is further examined in Section 3.3.

3.2 *The experience curve effect*

3.2.1 The experience curve effect and workers' innovations

Workers' innovations are indispensable, but how are they created? The experience curve effect gives a clue to this mechanism.

3.2.1.1 The theory of the experience curve effect

The experience curve effect states that the more often a task is performed, the lower the cost of doing it. Workers who perform repetitive tasks exhibit an improvement in performance as the task is repeated a number of times. The primary idea of the experience curve effect (the "learning curve effect" in earlier literature) dates back to Wright (1936), Hirsch (1952), Alchian (1963), and Rapping (1965). The importance of the learning curve effect was emphasized by Boston Consulting Group (BCG) in the late 1960s and early 1970s (e.g., BCG, 1972). The experience (or learning) curve effect has been applied in many fields, including business management, strategy, and organization studies (e.g., on airplanes, Wright, 1936; Asher, 1956; Alchian, 1963; Womer and Patterson, 1983; in shipbuilding, Searle and Goody, 1945; on machine tools, Hirsch, 1952; in metal products, Dudley, 1972; in nuclear power plants, Zimmerman, 1982; Joskow and Rozanski, 1979; in chemical products, Lieberman, 1984; Argote et al., 1990; in food services, Reis, 1991). More recently, it has also been applied to technology and policy analysis, particularly energy technologies (e.g., Yelle 1979; Dutton and Thomas, 1984; Hall and Howell, 1985; Lieberman, 1987; Argote and Epple, 1990; Criqui et al., 2000; McDonald and Schrattenholzer, 2001; van der Zwaan and Rablc, 2003, 2004; Miketa and Schrattenholzer, 2004; Papineau, 2006). An empirical problem of the experience curve effect is to distinguish dynamic learning effects from static economies of scale. After surveying empirical studies, Lieberman (1984) concluded that, in general, static scale economies are statistically significant but small in magnitude relative to learning-based economies (see also Preston and Keachie, 1964; Stobaugh and Townsend, 1975; Sultan, 1976; Hollander, 2003).

The experience curve effect is usually expressed by the following functional form:

$$C_N = C_1 N^{-(1-\alpha)} \qquad (1)$$

where C_1 is the cost of the first unit of output of a task, C_N is the cost of the nth unit of output, N is the cumulative amount of output and interpreted as experience of a worker engaging in the task, and α is a constant parameter ($0 < \alpha < 1$). $\frac{C_{2N}}{C_N}$ and $1 - \alpha$ are often called the progress ratio and learning rate, respectively. This log-linear functional form is most commonly used probably because of its simplicity and good fit to data. Empirical studies have shown that α is usually between 0.6 and 0.9. Studies by BCG in the 1970s showed that experience curve effects for various industries range from 10–25% cost reductions for every doubling of output (i.e., $0.58 \le \alpha \le 0.85$) (e.g., BCG, 1972). Dutton and Thomas (1984) present the distribution of progress ratios obtained from a sample of 108 manufacturing firms. The ratios mostly range from 0.7 to 0.9 (i.e., $0.48 \le \alpha \le 0.85$) and average 0.82 (i.e., $\alpha = 0.71$). OECD/IEA (2000) argues that industry-level progress ratios have a similar distribution as the firm-level ones shown in Dutton and Thomas (1984; see also, e.g., Hirsch, 1956; Womer and Patterson, 1983; Womer, 1984; Ayres and Martinas, 1992; Williams and Terzian, 1993).

The magnitude of α (or equivalently the progress ratio or learning rate) may be affected by various factors (e.g., Hirsch, 1956; Adler and Clark, 1991; Pisano et al., 2001; Argote et al., 2003; Sorenson, 2003; Wiersma, 2007). Nevertheless, the average α is usually observed to be almost 0.7 (i.e., a progress ratio of 0.8 and a learning rate of 0.3) as shown in BCG (1972), Dutton and Thomas (1984), and OECD/IEA (2000). It therefore seems reasonable to assume that α is 0.7 on average.

3.2.1.2 Information conveyed by experience

An important element that an experience conveys is information. By accumulating experiences of doing a task, a worker increases the amount of information known about the task and makes it more complete. In this sense, *N,* which indicates experience in equation (1), reflects the current amount of information a worker possesses about a task. Accumulated experiences will improve efficiency in implementing a task because the amount of information on the task increases. However, if other factors remain the same, the magnitude of improvement will diminish as *N* accumulates because the information on the task will approach saturation.

Let *I* be a set of the currently available maximum information on a task. Engaging in the task in a unit of period provides a subset of *I* to a worker. Engaging in more units of period (i.e., accumulating experience *N*) makes the information on the task the worker currently possesses ($\widetilde{I}$) approach *I* (i.e., the difference between $\widetilde{I}$ and *I* diminishes). A part of the subset of *I* the worker acquires in a unit of period will overlap the part of the subset of *I* the worker acquires in the next period. With more complete information, accordingly, efficiency will improve. Because $\widetilde{I} \rightarrow I$ as $N \rightarrow \infty$, then the magnitude of improvement will asymptotically decrease as *N* increases. Nevertheless, this asymptotical decrease may not be a simple process. Some piece of information may be easily obtainable and some other piece may not be, and some portion of information may have a relatively large impact on efficiency and other portions have small effects. The functional form that describes the asymptotical decrease of the magnitude of improvement will depend on interaction between these effects. The log-linear functional form $C_N = C_1 N^{-(1-\alpha)}$ fits empirical data well and is simple, and thus it has been used mostly for the experience curve effect.

3.2.1.3 Extending the concept of the experience curve effect

Because the essence of experience is that it conveys information, the experience curve effect can be extended to a wide variety of tasks. The tasks need not be limited to a worker's repeated actions, that is, tasks whose experiences are divided by periods. For example, consider that a human activity can be divided into many experiences, each of which is obtained by different workers. Each experience conveys a subset of information, and a part of the subset overlaps with subsets regarding other experiences. The experience curve effect will be applicable to this kind of task by interpreting *N* as a subset all worker experiences, so a task in a period whose experiences are divided by workers will be also applicable to the experience curve effect in the same way that a task performed by a worker whose experiences are divided by periods is. Extending this logic suggests that tasks applied to the experience curve effect should not be limited to the ones whose experiences are divided only by periods or workers. As long as the task is a human intellectual activity and its experiences are divided by factors other than periods or workers, the task will also be applicable to the experience curve effect because it has the common nature that each divided experience conveys only a subset of all the information that affects the worker's intellectual activities. Nevertheless, the concept of the experience curve effect should not be expanded infinitely. It can be applied only to the tasks of workers, the performances of which differ depending on the amount of information the worker has.

3.2.2 The experience curve effect in the technology input

3.2.2.1 Dispersively embodied accumulative innovation in capital

To understand the mechanism for the creation of non-accumulative innovations, it is first necessary to examine how workers are in contact with capital inputs and the accumulative innovations embodied in them at each production site. Any single machine or tool cannot embody all the accumulated innovations in human history. Only a portion of accumulated innovations are embodied in each machine or capital input. Furthermore, different types of machines or tools embody different kinds of accumulative innovations. This relationship between accumulative innovation and capital suggests that accumulative innovations are varied, divisible, and dispersed among capital inputs. If there are negative effects of congestion and redundancy in the embodiment of accumulative innovation in capital, this division of accumulative innovation improves productivity. Embodying more types of accumulative innovations in a machine or tool may make it a more general purpose machine or tool. In implementing a specific task, however, a general purpose machine or tool will be less useful and efficient than a specialized one because congestion and redundancy of the accumulative innovations will occur and reduce efficiency.

Suppose that there is only one economy in the world and that all workers in the economy are identical. Let *Y*(*A*, *K*, *L*) be a production function where *Y* is production, *A* is technology (accumulated innovations), *K* is capital input, and *L* is labor input. *A* can be interpreted as indicating the total amount of technology and, at the same time, the total number of varieties of technology in the economy. Let also τA be the portion of *A* embodied on average in a unit of capital where τ is a positive parameter. To incorporate the idea that the division of *A* mitigates congestion and redundancy and improves efficiency for production, the following assumption is introduced:

$$\frac{\partial Y(\tau, A, K, L)}{\partial \tau} < 0 \quad , \tag{2}$$

which indicates that the smaller the value of τ (i.e., the smaller the magnitude of congestion and redundancy), the larger the production *Y*.

On the other hand, if τ is too small, there is the possibility that a piece of *A* is not embodied in any part of *K*. Without embodying any portion of *A*, *K* is no longer a machine or tool but merely a pile of useless materials. Avoiding this abnormal situation requires a condition that any *K* must embody at least some portion of *A*. If $\tau < K^{-1}$, then the total amount of *A* used in the economy is $\tau AK < A$, and thus some portion of *A* is not embodied in any *K*, which indicates that the condition $K^{-1} \leq \tau$ is necessary for avoiding the abnormal situation and that $\tau = K^{-1}$ is the threshold value. As the rationale for the condition $K^{-1} \leq \tau$ with the threshold value $\tau = K^{-1}$, it is assumed here that the total differential $dY(\tau,A,K,L)$ with respect to *A* and τ is positive such that

$$dY(\tau,A,K,L) = \frac{\partial Y(\tau,A,K,L)}{\partial A} dA + \frac{\partial Y(\tau,A,K,L)}{\partial \tau} d\tau > 0 \tag{3}$$

for $\tau < K^{-1}$, and thus

$$\frac{dY(\tau,A,K,L)}{d\tau} = \frac{\partial Y(\tau,A,K,L)}{\partial A} \frac{dA}{d\tau} + \frac{\partial Y(\tau,A,K,L)}{\partial \tau} > 0 \tag{4}$$

for $\tau < K^{-1}$, which means that if τ is smaller than the threshold value K^{-1}, then the reverse effect of the amount of *A* on production is much larger than the effect of the division of *A* on production. If $K^{-1} \leq \tau$, then any portion of *A* is embodied in some *K*, and thereby $\frac{dA}{d\tau} = 0$ and $\frac{dY(\tau,A,K,L)}{d\tau} = \frac{\partial Y(\tau,A,K,L)}{\partial \tau} < 0$.

Combining the characteristics of τ shown in inequalities (2) and (4) indicates that the optimal value of τ is K^{-1}. As a result of the rational behavior of firms, the optimal dispersion of accumulative innovation in capital is obtained when $\tau = K^{-1}$, and thus the portion of A embodied on average in a unit of capital is always

$$K^{-1}A$$

in the economy. A worker faces $K^{-1}A$ units of accumulative innovations at any time when the worker uses a unit of capital.[1] Because A indicates the total number of varieties of technology as well as the total amount of technology, dispersively embodied A in K indicates that a worker faces K^{-1} of varieties of A when the worker uses a unit of capital.

3.2.2.2 Specialized or generalized machines or tools

Suppose that the amount of A is fixed; that is, no new variety of innovation is added. If K increases and A remains fixed, the proportion of A embodied in a unit of K becomes smaller because the proportion of A embodied in a unit of K is kept equal to $K^{-1}A$. A smaller $K^{-1}A$ means that machines or tools become more specialized because the purpose of a machine or tool embodying less A will be more limited. The types of machines or tools used will change even if A does not increase. If K increases in this case, machines and tools will become more specialized and vice versa. The variety and type of machines or tools, that is, how specialized or generalized they are, depend not only on A but also on K.

Note, however, that generalized does not necessarily mean advanced. On the contrary, general purpose machines or tools are more primitive, and conversely, special purpose ones are more advanced. To be general purpose, machines or tools must rely more on basic or core technologies, and many specialized functions will be downgraded.

3.2.2.3 Effective technology input

As argued in Section 3.2.1, the experience curve effect can be applied to a task as long as the task is an intellectual creative activity and the experiences can be divided by some factor. The experience curve effect is applicable to the activity of creating non-accumulative innovations to supplement imperfect accumulative innovations because (1) the activity is an intellectual creative activity and (2) the experiences can be divided by varieties of A in K a worker encounters. A worker encounters a portion of the accumulated innovations ($K^{-1}A$) when the worker uses a unit of capital. The portion of accumulated innovations conveys a subset of all the information on accumulated innovations and a part of the subset overlaps with those conveyed in other portions of accumulated innovations that other workers encounter.

A worker encounters a unique combination of varieties of accumulative innovations ($K^{-1}A$) per unit capital. Let N_A be a worker's average encounter frequency (i.e., the worker's experience) with each variety of accumulative innovations per unit capital in a period. As $K^{-1}A$ increases, the number of varieties per unit capital increases; thus, N_A will decrease because the probability of encountering each of the varieties in $K^{-1}A$ in a period decreases. The amount of $K^{-1}A$ therefore will be inversely proportional to a worker's experience on a variety per capital N_A such that

$$N_A = \beta_A \left(\frac{A}{K} \right)^{-1}$$

[1] In this paper, it is assumed that there is only one economy in the world. However, actually there are many smaller economies and a small economy may utilize only a small portion of A; i.e., the size of economy will matter to the optimal value of τ if there are many economies of various sizes. The problem of the size of economy as well as the problem of aggregation is discussed more in detail in Harashima (2009).

where β_A is a positive constant. Standardizing the worker's average encounter frequency β_A equal to unity, then

$$N_A = \left(\frac{A}{K}\right)^{-1}. \tag{5}$$

Let C_{A,N_A} be the amount of inefficiency resulting from imperfect technology (which is equivalent to imperfect accumulative innovations) embodied in capital when a worker utilizes a variety of accumulative innovations in $K^{-1}A$ in a period. C_{A,N_A} does indicates not the inefficiency initially generated by imperfect technology but the one remaining after being mitigated by workers' innovations. Costs increase proportionally to increases in inefficiency; thus, C_{A,N_A} also indicates costs. Conversely, C_{A,N_A}^{-1} can be interpreted as a productivity in supplementing imperfect technology by creating non-accumulative innovations when a worker utilizes a variety of accumulative innovations in $K^{-1}A$ in a period. The creation of non-accumulative innovations will increase as the frequency of a worker encountering a variety of accumulative innovations in $K^{-1}A$ increases (i.e., the productivity in supplementing imperfect technology by creating non-accumulative innovations will increase as the number of experiences increases). Hence, the inefficiency C_{A,N_A} will decrease as the encounter frequency increases. The experience curve effect indicates that inefficiency C_{A,N_A} declines (i.e., productivity C_{A,N_A}^{-1} increases) as a worker's average encounter frequency on a variety per unit capital (N_A) increases (i.e., $K^{-1}A$ becomes smaller) such that

$$C_{A,N_A} = C_{A,1} N_A^{-(1-\alpha)} \quad , \tag{6}$$

where $C_{A,1}$ is the inefficiency when $N_A = 1$. Note that α is the constant parameter ($0 < \alpha < 1$) used in equation (1).

In addition, the amount of technology input per unit capital will increase as C_{A,N_A}^{-1} increases (i.e., C_{A,N_A} decreases) because the inefficiency is mitigated by an increased amount of workers' innovations. Thus, the amount of technology input per unit capital when a worker uses a variety of accumulative innovations in $K^{-1}A$ will be directly proportional to C_{A,N_A}^{-1} (i.e., inversely proportional to C_{A,N_A}) such that

$$W_A \left(\frac{A}{K}\right)^{-1} = \frac{\gamma_A}{C_{A,N_A}} \quad , \tag{7}$$

where W_A is the amount of technology input per unit capital when a worker utilizes a unique combination of varieties of accumulative innovations in $K^{-1}A$, and γ_A is a positive constant (i.e., γ_A indicates the amount of technology input per unit capital when a worker utilizes a unique combination of varieties of accumulative innovations $K^{-1}A$ in a period when $C_{A,N_A} = 1$). Substituting equations (5) and (6) into equation (7) gives

$$W_A = \frac{\gamma_A}{C_{A,N_A}}\left(\frac{A}{K}\right) = \frac{\gamma_A}{C_{A,1}N_A^{-(1-\alpha)}}\left(\frac{A}{K}\right) = \frac{\gamma_A}{C_{A,1}\left(\frac{A}{K}\right)^{1-\alpha}}\left(\frac{A}{K}\right) = \frac{\gamma_A}{C_{A,1}}\left(\frac{A}{K}\right)^{\alpha} . \tag{8}$$

As discussed in Section 3.2.2.1, the amount of technology embodied in a unit capital is $K^{-1}A$. Because technology is imperfect, however, that level of technology input cannot be effectively realized. At the same time, the inefficiency resulting from the imperfections is mitigated by non-accumulative innovations created by ordinary workers even though it is not completely removed. Equation (8) indicates that the magnitude of mitigation depends on $K^{-1}A$, and that, with the mitigation, technology input per unit capital is effectively not equal to $K^{-1}A$ but directly proportionate to $W_A = \frac{\gamma_A}{C_{A,1}}\left(\frac{A}{K}\right)^{\alpha}$. By equation (8), therefore, the effective technology input per unit capital ($\widetilde{A}$) is

$$\widetilde{A} = \upsilon_A W_A = \omega_A\left(\frac{A}{K}\right)^{\alpha} \tag{9}$$

where υ_A and ω_A are positive constant parameters and $\omega_A = \frac{\upsilon_A \gamma_A}{C_{A,1}}$.

3.2.3 The experience curve effect in the labor input

The task of mitigating the inefficiency resulting from fragmented and incomplete information caused by the division of labor satisfies the condition for applying the experience curve effect (Section 3.2.1). As shown in Section 3.1.3, workers' innovations reduce this inefficiency. In addition, production processes are divided by workers as part of the division of labor. Each worker encounters only a portion of the whole production process, a portion of the process conveys only a portion of information on the whole production process, and the information overlaps partially with that on other processes that other workers encounter. Hence, the experience curve effect can be applied to this task. Because labor is divided fully at the global level, inefficiency mitigation activities are correlated at the global level.

Let N_L be the production processes a worker encounters (i.e., the experience of a worker); it indicates the proportion of all production processes in the economy (N), which is here normalized such that $N = 1$. A proportion of the production process conveys a subset of all the information on the production process, and a part of the subset overlaps with subsets of information on processes that other workers encounter. Remember, in this discussion, I am assuming that there is only one economy in the world and that all workers are identical. Thus, because the experience of a worker (N_L) is inversely proportionate to the number of workers, then

$$N_L = L^{-1}\beta_L$$

where L is the number of workers in the economy and β_L is a constant. $\beta_L\left(= N_L L\right)$ indicates the total of all production processes in the economy such that $\beta_L = N$. Because $N = 1$, then

$$N_L = L^{-1} \quad . \tag{10}$$

Let C_{L,N_L} be the magnitude of inefficiency in a worker's labor input caused by fragmented and incomplete information when each worker's experience is N_L. C_{L,N_L} indicates not the inefficiency initially generated by fragmented and incomplete information but the inefficiency that remains after mitigation by a worker's innovations. Costs will increase proportionally with increases in inefficiency, and thus C_{L,N_L} also indicates costs. C_{L,N_L}^{-1} can be interpreted as a productivity in a worker's labor input, which increases as the amount of mitigation by the worker's innovations increases.

C_{L,N_L} increases as the amount of individually available information (i.e., experience) increases. The increased amount of information enables a worker to discover more correct mechanisms of the production processes, and this discovery reduces the inefficiency in a worker's labor input. As mentioned previously, the experience curve effect can be applied to this inefficiency mitigation mechanism. The experience curve effect indicates that C_{L,N_L} declines as the experience of a worker (N_L) increases (i.e., the number of workers deceases) such that

$$C_{L,N_L} = C_{L,1} N_L^{-(1-\alpha)} \quad , \tag{11}$$

where $C_{L,1}$ is the inefficiency when N_L = 1 (i.e., N_L = N and L = 1). Note again that α is the constant parameter ($0 < \alpha < 1$) used in equation (1).

In addition, because the amount of a worker's provision of labor input increases as productivity (C_{L,N_L}^{-1}) increases (i.e., C_{L,N_L} decreases), then the amount of a worker's provision of labor input ($L^{-1}W_L$) is directly proportional to C_{L,N_L}^{-1} (i.e., inversely proportional to C_{L,N_L}) such that

$$\frac{W_L}{L} = \frac{\gamma_L}{C_{L,N_L}} \quad , \tag{12}$$

where W_L is the total amount of workers' provision of labor input that is supplemented by worker's innovations to mitigate the inefficiency resulting from fragmented and incomplete information, and γ_L is a constant (i.e., γ_L indicates the output per worker in a period when $C_{L,N_L} = 1$). Substituting equations (10) and (11) into equation (12) gives

$$W_L = \frac{\gamma_L}{C_{L,N_L}} L = \frac{\gamma_L}{C_{L,1} N_L^{-(1-\alpha)}} L = \frac{\gamma_L}{C_{L,1} L^{1-\alpha}} L = \frac{\gamma_L}{C_{L,1}} L^{\alpha} . \tag{13}$$

The inefficiency caused by fragmented and incomplete information constrains the labor provision by workers. As division of labor is widened (i.e., as L increases), the labor provision by workers is more constrained. The inefficiency, however, is mitigated by innovations created by workers, but it cannot be completely removed by workers' innovations. Hence, the labor input that is effectively provided by workers is not simply proportional to L. Equation (13) indicates that, instead of L, the labor input effectively provided by workers is directly proportional to $W_L = \frac{\gamma_L}{C_{L,1}} L^{\alpha}$; thus, the effective labor input $\widetilde{L}$ is

$$\widetilde{L} = \upsilon_L W_L = \omega_L L^{\alpha} \quad , \tag{14}$$

where υ_L and ω_L are positive constant parameters and $\omega_L = \frac{\upsilon_L \gamma_L}{C_{L,1}}$.

3.2.4 The experience curve effect and the capital input

As with $\widetilde{A}$ and $\widetilde{L}$, an inefficiency with regard to the capital input K may exist, and this inefficiency may be solved by intellectual activities of workers. If such inefficiency exists, the effective capital input would not be equal to K. However, I was unable to find a factor that significantly necessitates a worker's intellectual activities to lessen inefficiencies in utilizing capital, in particular inefficiencies that result from imperfectness or incompleteness of information on capital. Therefore, I have assumed that capital input does not necessitate workers' innovations. However, capital input is constrained by another element that is basically irrelevant to workers' intellectual activities. It is impossible for each worker to use all capital inputs existing in the economy; each worker can access only a fraction of the total amount. This accessibility constraint sets bounds to the use of capital. Nevertheless, the accessibility is basically irrelevant in terms of worker innovation because accessibilities of workers in the world are not correlated with each other at the global level and thus it is not difficult for a worker to find a correct way to access capital inputs when an unexpected incident occurs. Therefore, information on accessibility is not incomplete, and it is enough for a worker to know only local information with regard to accessibility to capital. Therefore, there is little differentiation among workers in finding correct ways to access capital inputs, and as a consequence, there is little differentiation in the workers' experiences.

Machines or tools are not necessarily in constant operation during production; they are idle during some periods. A worker often uses various machines or tools in turn in a period, or equivalently several workers often use the same machine or tool in turn in a period. Let σK be the portion of K used by a worker on average where $\sigma \left(0 < \sigma \leq 1\right)$ is a positive parameter. Because the total sum of K used in the economy must not be smaller than K, $K \leq \sigma KL$, $L^{-1} \leq \sigma$, and thereby $L^{-1} \leq \sigma \leq 1$ for $1 \leq L$. It is highly likely that production increases if more K is used per worker, in which case

$$\frac{\partial Y(\sigma,A,K,L)}{\partial \sigma} > 0 \quad . \tag{15}$$

Condition (15) and the constraint $L^{-1} \leq \sigma \leq 1$ lead to a unique steady state value of σ such that $\sigma = 1$, which indicates that each worker uses all K existing in the economy. Clearly, that is impossible—accessibility to capital is not limitless. Even if a worker wants to use K installed at a distant location, it is usually meaningless to do so because it is too costly. Thus, it is highly likely that there is a boundary of accessibility with regard to location. A worker can use only a small portion of K installed in the small area around the worker. That is, the value of the parameter σ has an upper bound such that

$$L^{-1} \leq \sigma \leq \bar{\sigma} \quad , \tag{16}$$

where $\bar{\sigma} \left(0 < \bar{\sigma} < 1\right)$ is a positive constant. With the upper bound $\bar{\sigma}$, by conditions (15) and (16), the optimal portion of K used by a worker on average ($\widetilde{K}$) for $1 \leq L$ is

$$\widetilde{K} = \bar{\sigma} K \, . \tag{17}$$

The parameter $\bar{\sigma}$ represents a worker's accessibility limit to capital with regard to location.[2] The average value of $\bar{\sigma}$ in the economy will depend on the availability of physical transportation facilities. Location constraints, however, are not limited to physical transportation facilities. For example, law enforcement, regulations, the financial system, and other factors will also influence accessibility. The value of $\bar{\sigma}$ reflects the combined effects of all of these factors. The values of $\bar{\sigma}$ with regard to workers who are obliged to work at a designated location using fixed machines in a factory (e.g., workers in manufacturing industries) may be nearly identical. However, values for workers in other jobs (e.g., in service industries) will be heterogeneous depending on conditions. Even in manufacturing industries, workers engage in a variety of activities (e.g., negotiating with financial institutions or marketing), so the values of $\bar{\sigma}$ will also be heterogeneous in manufacturing industries.

Suppose that the density of capital per unit area is identical in the industrial area in the economy with an upper bound of $\bar{\sigma}$.[3] An increase of the total sum of K indicates an increase of the density of K in the industrial area; thus, the portion of K used by a worker also increases at the same rate as K. On the other hand, an increase of the total sum of L does not indicate any change of the density of K in the industrial area, and the portion of K used by a worker does not change.

3.2.5 Related theories

3.2.5.1 Learning-by-doing

The theory of learning-by-doing originated in Arrow (1962), who argues that productivity is improved by workers' regularly repeating the same type of action through practice, self-perfection, and minor innovation. Arrow-type growth models assume that productivity is proportionate to accumulated investments in capital or production, which represent the accumulated effects of workers' learning-by-doing (e.g., Sheshinski, 1967; Romer, 1986). If accumulated experiences obtained through learning-by-doing are proportionate not to accumulated innovations (A) but to accumulated past investments in capital or production and are heterogeneous across economies, current significant income differences across economies, which are difficult to explain by attributing the fundamental cause to A because A is homogenous among economies, can be explained. Arrow (1962) argues that different economies have different production functions because of heterogeneous amounts of accumulated learning-by-doing.

The concept of learning-by-doing is similar to the concept of the effective technology and labor inputs $\tilde{A}$ and $\tilde{L}$ in some aspects. They both focus on activities of ordinary workers. Indeed, some researchers base the foundation of the experience curve effect on the theory of learning-by-doing (e.g., Hall and Howell, 1985; Adler and Clark, 1991; Nemet, 2006). However, the concepts are different in the following important aspects.

- Learning-by-doing mostly consists of activities to learn already-uncovered knowledge, technologies, or ideas, but the creation of non-accumulative innovations by workers consists only of activities to create something new.
- Experiences obtained through learning-by-doing in Arrow-type growth models accumulate in the economy, but non-accumulative innovations created by workers do not accumulate.
- The amount of accumulated learning-by-doing in Arrow-type growth models is proportionate to accumulated investments in physical capital and production. The amount of non-accumulative innovations to supplement imperfect accumulated innovations is

[2] If there are many economies with various sizes, each economy's value of $\bar{\sigma}$ may be different. The effect of the size of economy on $\bar{\sigma}$ is discussed in Harashima (2009).

[3] An industrial area is considered here to be an area that is appropriate for economic activities and excludes deserts, deep forests, mountains, and other inaccessible areas. This concept is important when we consider the size of economy, which is examined in detail in Harashima (2009).

proportionate to accumulated innovations (*A*) and inversely proportionate to the physical capital input (*K*). The amount of non-accumulative innovations to mitigate the inefficiency resulting from fragmented and incomplete information is proportionate to the labor input (*L*).

3.2.5.2 Human capital

Human capital usually refers to a worker's knowledge and skills that help increase productivity and performance at work and that are obtained by intentionally investing in education and training. The concept of human capital in the modern neoclassical economic literature dates back to Mincer (1958) and has been studied widely since Becker (1962, 1964). Human capital is similar to physical capital. Anyone can invest in it, and it is substitutable for physical capital and labor. Becker (1962) argues that investing in human capital means all activities that influence future real income through the embedding of resources in people. Investing in human capital takes the forms of formal schooling, on-the-job training, off-the-job training, medical treatment, and similar activities (e.g., Weisbroad, 1966; Lynch, 1991). Some researchers have argued that the currently observed international differences in investments and growth rates are closely related with human capital (e.g., Lucas, 1990; Barro, 1991; Benhabib and Spiegel, 1994).

The concept of human capital is similar to the concept of effective labor and technology inputs ($\widetilde{A}$ and $\widetilde{L}$) as well as learning-by-doing concepts in some aspects. These concepts commonly focus on the activities of ordinary workers. In Becker (1964), general and specific human capital inputs are distinguished because general human capital is useful not only with current workers but also with potential workers. Specific human capital in this sense is useful only with a current worker in a current job. Although researchers have argued that generating convincing examples of meaningful specific human capital is difficult (e.g., Lazear, 2003), specific human capital in the sense of Becker (1964) may consist partly of non-accumulative innovations. However, the concepts are different in the following fundamental aspects.

- A worker's human capital mostly consists of knowledge, technology, or ideas that have already been uncovered by other persons, but the creation of non-accumulative innovations by workers consists only of activities to create something new.
- Human capital obtained through education and training accumulates, but non-accumulative innovations do not.
- The amount of human capital is proportionate to variables that are unrelated to *A*, *K*, or *L* (e.g., periods of education or training). The amount of non-accumulative innovations to supplement imperfect accumulated innovations is proportionate to accumulated innovations (*A*) and inversely proportionate to physical capital input (*K*). The amount of non-accumulative innovations to mitigate the inefficiency resulting from fragmented and incomplete information is proportionate to the labor input (*L*).

These differences indicate that, as with learning-by-doing, the core concepts of human capital and effective technology and labor inputs are fundamentally different.

The concept of effective labor and technology inputs focuses more specifically on creativity and non-accumulative innovations. The concept of human capital appears infinitely elastic, and its broad but ambiguous nature may confuse arguments. Many studies of human capital have narrowed the scope to education or training to avoid this ambiguity, although the concept of education still appears too broad for analyses of economic growth (e.g., Krueger and Lindahl, 2001).

3.3 Production function

3.3.1 Effective production function

Suppose that production requires some strictly positive minimum amounts of *A*, *K*, and *L*. In addition, suppose that *A*, *K*, and *L* each do not exhibit increasing marginal product; that is, $\frac{\partial^2 f(A,K,L)}{\partial A^2} \le 0$, $\frac{\partial^2 f(A,K,L)}{\partial K^2} \le 0$, and $\frac{\partial^2 f(A,K,L)}{\partial L^2} \le 0$. If $\lim_{A\to\infty} \frac{\partial^2 f(A,K,L)}{\partial A^2} = 0$, $\lim_{K\to\infty} \frac{\partial^2 f(A,K,L)}{\partial K^2} = 0$, and $\lim_{L\to\infty} \frac{\partial^2 f(A,K,L)}{\partial L^2} = 0$, then for sufficiently large *A*, *K*, and *L*, the production function is approximated by the production function in which any of *A*, *K*, and *L* exhibits constant marginal product such that

$$Y = \psi_1 (A + \psi_2)(K + \psi_3)(L + \psi_4) + \psi_5 \quad , \tag{18}$$

where ψ_i (i = 1, 2, 3, 4, 5) are constants. Here, by the assumption that production requires some strictly positive minimum amounts of *A*, *K*, and *L*, then $f(0,K,L)=0$, $f(A,0,L)=0$, and $f(A,K,0)=0$. Among the approximated production functions (18), the production function that also satisfies this minimum requirement condition is

$$Y = \psi_1 AKL \quad .$$

If ψ_1 is standardized such that $\psi_1 = 1$, then

$$Y = AKL \quad . \tag{19}$$

Production function (19) appears intuitively understandable. Each of *L* workers uses *K* capital inputs per worker with *A* amount of technologies utilized in each *K*.[4] However, production function (19) cannot be realized as it is, because there are various constraints caused by various imperfections, as I argued in Section 3.2. The effective amounts of technology and labor inputs are not *A* and *L* but $\widetilde{A}$ and $\widetilde{L}$, and the portion of *K* usable for a worker on average is not *K* but $\widetilde{K}$. Hence, the approximated production function is effectively

$$Y = \widetilde{A}\widetilde{K}\widetilde{L} \quad . \tag{20}$$

Here, by equations (9), (14), and (17),

$$\widetilde{A}\widetilde{K}\widetilde{L} = \omega_A \left(\frac{A}{K}\right)^{\alpha} \bar{\sigma} K \omega_L L^{\alpha} = \bar{\sigma}\omega_A \omega_L A^{\alpha} K^{1-\alpha} L^{\alpha} \quad . \tag{21}$$

Rational firms utilize inputs fully so as to maximize *Y*, and by equations (20) and (21), the approximate effective production function (AEPF) can be represented as

$$Y = \bar{\sigma}\omega_A \omega_L A^{\alpha} K^{1-\alpha} L^{\alpha} \quad . \tag{22}$$

3.3.2 The approximate effective production function

AEPF has the following properties, which have been widely assumed for production functions and are consistent with data across economies and time periods: a Cobb-Douglas functional

[4] Remember that all workers are assumed to be identical.

form, a labor share of about 70%, and strict Harrod neutrality. The function therefore also has decreasing marginal products of labor, capital, and technology.

3.3.2.1 Cobb-Douglas functional form

The rationale and microfoundation of the Cobb-Douglas functional form have been long argued, but no consensus has been reached. For example, Jones (2005) argues that Cobb-Douglas production functions are induced if it is assumed that ideas are drawn from Pareto distributions. Growiec (2008), however, shows that Clayton-Pareto class of production functions that nest both the Cobb-Douglas functions and the CES are induced by assuming that each of the unit factor productivities is Pareto-distributed, dependence between these marginal distributions is captured by the Clayton copula, and that local production functions are CES. AEPF provides an alternative rationale and microfoundation of the Cobb-Douglas functional form. AEPF is the typical Cobb-Douglas production function, and the keys of its Cobb-Douglas functional form are workers' innovations and the experience curve effect.

3.3.2.2 A 70% labor share

The parameter α indicates the labor share in the distribution of income. Data in DME show that labor share is about 70% (see e.g., OECD.Stat Extracts[5]). No persuasive rationale has been presented on why the labor share is usually about 70%, but AEPF can offer one. In AEPF, the value of α is derived from the experience curve effect, and the average value of α has been shown to be about 70% in many empirical studies on the experience curve effect (e.g., Hirsch, 1956; Womer and Patterson, 1983; Dutton and Thomas, 1984; Womer, 1984; Ayres and Martinas, 1992: Williams and Terzian, 1993; OECD/IEA, 2000), which implies that workers' average rate of reducing inefficiencies is bounded. This boundary probably exists because newly added information decreases as the number of experiences increases and also because the marginal efficiency in a worker's analyzing, utilizing, and managing information (i.e., in creating innovations) decreases as the amount of information increases.

3.3.2.3 Strict Harrod neutrality and balanced growth

Because AEPF is a Cobb-Douglas production function, any of Harrod, Hicks, and Solow neutralities can be assumed as the type of technology change embodied in it. However, AEPF is Harrod neutral in the strict sense such that a unit of A is neither $A^{-\frac{\alpha}{1-\alpha}}$ (Solow neutral) nor $A^{-\alpha}$ (Hicks neutral) but A^{-1} because a unit of A is defined before the functional form of AEPF is induced using the experience curve effect. This strict Harrod neutrality is a necessary condition for a balanced growth path. In the balanced growth equilibrium, the capital intensity of the economy $Y^{-1}K$ is kept constant, and $L^{-1}Y$, $L^{-1}K$, and A grow at the same rate. Because AEPF is strictly Harrod neutral, it is possible for a growth model based on AEPF to achieve a balanced growth path.

At first glance, the essential factor behind the strict Harrod neutrality in AEPF appears to be that both $\widetilde{A}$ and $\widetilde{L}$ are subject to workers' intellectual activities and the experience curve effect. However, this view is somewhat superficial. In a deeper sense, there is a more essential factor. For strict Harrod neutrality to be achieved, it is necessary that both AEPF with constant L and AEPF with constant A be homogeneous of degree 1 with regard to (A and K) and (K and L), respectively. These conditions are satisfied in AEPF because $\widetilde{A}$ is $\omega_A\left(\frac{A}{K}\right)^{\alpha}$, and $\widetilde{A}$ therefore is not proportionate simply to A but to $K^{-1}A$. That is, strict Harrod neutrality requires various types of accumulative innovations in A to be dispersed in K, which means that

[5] http://stats.oecd.org/Index.aspx

A and K are closely related (like two sides of the same coin). Production (Y) increases at the same rate as A and K; thus, the capital intensity ($Y^{-1}K$) is constant.

As shown in Section 3.2, the nature of dispersive accumulative innovations originates in the optimization of firms to minimize inefficiencies caused by congestion and redundancy of A (i.e., to maximize effects of the division of A). Because technology input is optimal when capital is as specialized as possible, then capital is actually as specialized as possible by the optimizing behaviors of firms, which implies that the very essence of the strict Harrod neutrality and the balanced growth path lies in the optimizing behaviors of rational firms.

3.3.3 AEPF and Hayek's view of knowledge

As summarized in Section 2, knowledge of unexpected problems and corresponding innovations is an important element in the knowledge of the particular circumstances of time and place. Therefore, AEPF can be regarded as a model that is built on and correctly reflects Hayek's view of knowledge.

4 WORKERS' INNOVATIONS IN SPEs

4.1 The nature of the knowledge

An important aspect of the knowledge of unexpected problems and the corresponding workers' innovations is that the knowledge consists of not only simple data but also of a great deal of descriptive information, including ambiguous impressions, feelings, perceptions, guesses, intuitions, and hypotheses. The term "unexpected" is key here. Because an unexpected problem is not known in advance, the worker in a specific situation examines the problem using human intelligence. In some cases, these examinations may be implemented unconsciously. The knowledge includes information on all the results and processes of the examinations implemented through human intelligence and other related information. Therefore, the characteristics of unexpected problems and the corresponding innovations cannot be described by a few simple predetermined symbols or data inputs. A great deal of descriptive information is necessary to explain and understand this type of knowledge.

The nature of this type of knowledge puts an important constraint on its use: computers are of limited use in dealing with this type of knowledge. Computers can deal with phenomena that are already known and are categorized *ex ante* as standardized simple patterns, symbols, or data if the computer is pre-programmed to deal with these patterns, symbols, or data. At present, computers cannot deal with elements that have not been pre-programmed, which include the previously mentioned ambiguous impressions, feelings, perceptions, and intuitions that workers use when dealing with unexpected problems.

4.2 Incentives

4.2.1 Incentive and productivity

Workers' innovations are an important element of productivity, but most workers will generate innovations only when given an incentive. The strength of the incentive can be measured by the amount of reward or punishment a worker receives, and if rewards or punishments are increased, the incentive will increase. In this paper, the incentive for a worker to generate innovations is modeled as

$$\frac{\mu_1\tilde{\alpha} - \mu_2\left(-\tilde{\alpha}\right)}{2} = \frac{\mu_1 + \mu_2}{2}\tilde{\alpha} \quad ,$$

where $\mu_1 \left(0 \le \mu_1 \le 1\right)$ is the subjective probability that a worker receives a reward for generating an innovation (e.g., a wage increase); $\mu_2 \left(0 \le \mu_2 \le 1\right)$ is the subjective probability that a worker receives a punishment for not generating an innovation (e.g., a wage decrease); and $\tilde{\alpha} \left(0 \le \tilde{\alpha} \le 1\right)$ is the worker's share in the increased income owing to a worker's innovation. Therefore, μ_1 and μ_2 represent the likelihood and $\tilde{\alpha}$ represents the size of the rewards and punishments. $\mu_1 = 1$ ($\mu_2 = 1$) indicates that a reward (punishment) is 100% certain for generating (not generating) an innovation, and a value of 0 indicates that there is no possibility of a reward (punishment). Thereby, if rewards and punishments are both entirely certain, $\frac{\mu_1 + \mu_2}{2} = 1$, and if rewards and punishments are both impossible, $\frac{\mu_1 + \mu_2}{2} = 0$.

Suppose that an entrepreneur gives the rewards and punishments to workers surely based on information about the workers' generation of innovations. Then, the subjective probability and incentive of a worker depend on the quality of the information the entrepreneur can obtain. If the information is perfectly obtained, $\frac{\mu_1 + \mu_2}{2} = 1$; if the information is imperfect, $0 \le \frac{\mu_1 + \mu_2}{2} < 1$. In particular, if the entrepreneur obtains no information, then $\frac{\mu_1 + \mu_2}{2} = 0$. Therefore, the incentive $\frac{\mu_1 + \mu_2}{2}\tilde{\alpha}$ can be substituted with

$$\mu \tilde{\alpha}$$

where μ ($0 \le \mu \le 1$) is the subjective probability that the information the entrepreneur obtains is perfect. $\mu = 1$ indicates that workers are 100% confident of the perfectness of the information, and $\mu = 0$ indicates that workers are completely confident the entrepreneur obtains no information. Obviously, if $0 < \mu < 1$, there is some uncertainty about the perfectness of the information.

As shown in Section 3, $C_{A,1}^{-1}$ represents the productivity of supplementing imperfect technology by creating non-accumulative innovations, and $C_{L,1}^{-1}$ is the productivity of a worker's labor input, which increases as the amount of mitigation by the worker's innovations increases. Because the productivity of generating a worker's innovation depends on incentives, $C_{A,1}^{-1}$ and $C_{L,1}^{-1}$ are functions of $\tilde{\alpha}$ and μ such that $\left[C_{A,1}(\mu \tilde{\alpha})\right]^{-1}$ and $\left[C_{L,1}(\mu \tilde{\alpha})\right]^{-1}$.

If the incentive is stronger, a worker works harder to generate innovations and productivity increases. Hence, productivities $\left[C_{A,1}(\mu \tilde{\alpha})\right]^{-1}$ and $\left[C_{L,1}(\mu \tilde{\alpha})\right]^{-1}$ will be enhanced as μ and $\tilde{\alpha}$ increase, such that

$$\frac{\partial \left[C_{A,1}(\mu \tilde{\alpha})\right]^{-1}}{\partial \mu} > 0 \quad \text{and} \quad \frac{\partial \left[C_{L,1}(\mu \tilde{\alpha})\right]^{-1}}{\partial \mu} > 0 \quad \text{for} \quad 0 \le \mu < 1 \quad , \tag{23}$$

and

$$\frac{\partial \left[C_{A,1}(\mu \tilde{\alpha})\right]^{-1}}{\partial \tilde{\alpha}} > 0 \quad \text{and} \quad \frac{\partial \left[C_{L,1}(\mu \tilde{\alpha})\right]^{-1}}{\partial \tilde{\alpha}} > 0 \quad \text{for} \quad 0 \le \tilde{\alpha} < 1 \quad . \tag{24}$$

Here, let productivity $\bar{\sigma}\omega_A\omega_L$ in AEPF be Ω. By equation (22),

$$Y = \Omega A^{\alpha} K^{1-\alpha} L^{\alpha} \quad . \tag{25}$$

Because $C_{A,1}^{-1}$ and $C_{L,1}^{-1}$ are functions of $\mu\tilde{\alpha}$, then, by equations (8), (9), (13) and (14), productivity Ω is also a function of $\mu\tilde{\alpha}$, such that $\Omega(\mu\tilde{\alpha})$, and by inequalities (23) and (24),

$$\frac{\partial \Omega}{\partial \mu} > 0 \quad \text{for} \quad 0 \le \mu < 1$$

and

$$\frac{\partial \Omega}{\partial \tilde{\alpha}} > 0 \quad \text{for} \quad 0 \le \tilde{\alpha} < 1 \quad .$$

It is highly likely that $\Omega(0)$ is very low and far smaller than $\Omega(\mu\tilde{\alpha})$ for $\mu \approx 1$ and $\tilde{\alpha} = \alpha$ where, as shown in equation (25), α indicates the labor share in the distribution of income in the AEPF and is about 0.7 in most DMEs (see e.g., OECD.Stat Extracts[6]). With little incentive, workers will generate little innovation and the level of production will remain very low. Nevertheless, even if the value of $\Omega(0)$ is very low, it will not be zero because even if there is no incentive ($\mu\tilde{\alpha} = 0$), a worker may generate innovations for a variety of reasons, including personal curiosity, an unconscious sense of duty, to relieve boredom, or attempt to gain the admiration of other workers.[7] In AEPF, the value of $\Omega(0)$ depends on the values of $C_{A,1}(0)$, $C_{L,1}(0)$, γ_A, and γ_L.

4.2.2 Incentives in DMEs

The AEPF indicates that higher values of ω_A and ω_L yield higher levels of production. Entrepreneurs can gain more income if workers generate more innovations. Therefore, entrepreneurs seek out workers' innovations that bring in profits and they fully pursue exploiting the opportunities that workers' innovations provide. Entrepreneurs will make efforts to obtain the knowledge and provide sufficient incentives to workers. To offer incentives to workers, entrepreneurs will explicitly or implicitly promise to give workers a share of the increased income gained by the workers' innovations as a reward. Of course, the division of labor requires discipline, and the role of an individual worker in a production process is limited. Workers' activities deviating from their designated roles are usually prohibited. Nevertheless, within the given role of an individual worker, entrepreneurs will encourage workers to innovate.

In a DME, there are many entrepreneurs dispersed across many production sites, and these entrepreneurs act independently of each other while attempting to fully exploit the opportunities that workers' innovations provide. Thanks to decentralization, therefore, entrepreneurs, as a group, recognize all pieces of the knowledge and provide sufficient incentive to all workers located at all of the widely dispersed production sites. The value of μ will be maximized through competition among entrepreneurs, and thereby high μ ($\mu \approx 1$) is guaranteed.

In DMEs, wages are determined through competition, and the overall worker's share converges at α at equilibrium if the production function is the Cobb–Douglas type, which is the case in the AEPF. Hence, the worker's share for the extra income gained by workers' innovations ($\tilde{\alpha}$) will also converge at α. Therefore, in DMEs with $\mu \approx 1$,

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[6] http://stats.oecd.org/Index.aspx

[7] An example of incentives other than wage increases and promotions is those in a war economy. The reward for workers is victory, which can be a strong incentive for workers to generate innovations if the war is strongly supported by the workers.

$$\mu\tilde{\alpha} \approx \alpha \quad .$$

Because α is about 0.7 in most DMEs (see e.g., OECD.Stat Extracts[8]), the incentive for workers to generate innovations will be far above zero. Hence, workers will generate a sufficiently large number of innovations in DMEs, and thereby DMEs intrinsically can function sufficiently productively.

4.2.3 Incentives in SPEs

Unlike the case in DMEs, the incentive for workers to implement intellectual activities is not spontaneously generated in SPEs but needs to be intentionally created by a CPB because of centralization. In Lange's model, the incentive for innovation is not explicitly described. If anything, the incentive is not supposed to be a necessary element in Lange's model because workers are described as robot-like beings who only implement routine non-intellectual tasks according to predetermined rules. On the other hand, the AEPF indicates that workers' intellectual activities are indispensable, and without an incentive for workers to generate innovations (i.e., if $\Omega[0]$), production is far below the level that is achieved with incentives (i.e., $\Omega[\alpha]$). The AEPR, therefore, indicates that an SPE in the pure Lange-type model cannot function as productively as a DME, and the model should be modified to incorporate a mechanism that gives workers the incentive to innovate.

For a sufficient incentive (i.e., for a CPB to achieve μ = 1), *ex post* rewards (or punishments) must be given to a worker who generated (or did not generate) an innovation. Correctly providing *ex post* rewards and/or punishments requires that a CPB, which centrally makes decisions on wages, promotions, demotions, and other aspects of personnel management, correctly knows and evaluates each worker's innovations. Therefore, knowledge about all of the unexpected problems and the corresponding workers' innovations in all the dispersed production sites must be perfectly reported and transmitted by managers at the sites to the CPB. If the knowledge is not perfectly transmitted, wages will be distorted.

Nevertheless, the SPE could function well if the incentive for workers to innovate were replaced with a simple rule and the CPB could easily monitor the implementation of the rule. However, rules cannot substitute for incentives because of the previously discussed nature of the knowledge. The rule would need to be unconditionally implemented by workers without the utilization of their intelligence—otherwise, it is not a rule. Thus, rules cannot replace incentives. Therefore, for an SPE to function as productively as a DME, Lange's model must be modified to incorporate a mechanism by which all managers located in dispersed production sites report the knowledge perfectly to the CPB.

4.3 Transmission and utilization of knowledge

Because of the nature of knowledge that was discussed in Section 4.1, the following condition needs to be satisfied for knowledge to be perfectly transmitted to the CPB.

Condition 1: Managers must not be considered to be robot-like; they must be considered as human beings capable of implementing intellectual activities.

For managers to fully know and evaluate unexpected problems and the corresponding workers' innovations, they need to understand how a worker measured, analyzed, and evaluated an unexpected problem and then generated the corresponding innovations. Managers may have to almost duplicate the processes of workers' intellectual activities to fully understand the

[8] http://stats.oecd.org/Index.aspx

knowledge, which is not a job that can be implemented according to predetermined rules. Therefore, managers must be capable of implementing intellectual activities.

Furthermore, managers must be able to correctly and completely report the knowledge to the CPB. Knowledge of something does not necessarily guarantee that it can be correctly reported to others. Reporting knowledge requires intelligence to adequately communicate to others. Managers therefore must be able to use their intelligence not only to understand the knowledge but also to communicate it to the CPB.

In addition to Condition 1, the following condition also needs to be satisfied for the perfect transmission of the knowledge to the CPB.

Condition 2: Managers must be given sufficient incentive to completely and correctly report the knowledge to the CPB.

Like workers, managers will not correctly report the knowledge to the CPB without incentives. Rewards and/or punishments need to be given to managers according to their performances on the transmission of the knowledge. Giving rewards and/or punishments necessitates that the CPB obtains knowledge on the performance of managers.

Even if Conditions 1 and 2 are satisfied and the knowledge is correctly reported, the knowledge is useless if it is not utilized by the CPB. Therefore, the following third condition must also be satisfied.

Condition 3: The CPB must process the sum of the knowledge reported from all managers.

4.4 Failure of SPEs

An SPE cannot match a DME in terms of productivity unless the above three conditions are satisfied. The three conditions are linked to each other and thus each of them is satisfied only when all of them are simultaneously satisfied because rewards and/or punishments will not otherwise be properly given. That, however, is not an easy task, especially in the case of Condition 3. Unlike Conditions 1 and 2, Condition 3 cannot be satisfied with "minor" modifications of the SPE scheme.

The CPB faces a serious problem in utilizing the reported knowledge because the volume of the knowledge it must process will far exceed its capacity to process the knowledge for two main reasons. First, the knowledge consists of not only simple symbols and data but also of descriptive explanations that include ambiguous impressions, perceptions, and intuitions, and a computer system intrinsically cannot handle this vast amount of knowledge. Second, a relatively small number of personnel in the CPB will need to handle reports from millions of managers, each of which contains the reports of many workers. That is, the CPB must handle the results of the intellectual activities of tens of millions or more workers who deal with billions or more unexpected problems and generate billions or more corresponding innovations every day. In essence the CPB needs to duplicate the sum of the intellectual activities that tens of millions of managers and workers implement. Each worker in the CPB would have the impossible task of correctly making decisions on wage settings and other aspects of personnel management by completely utilizing the reported knowledge on each of the tens of millions or more workers and managers.

Clearly, the CPB cannot sufficiently process all of the knowledge and utilize it to offer proper incentives for all managers and workers because there is an upper boundary on the amount of the knowledge a human being can deal with in a given period and on the number of workers at the CPB. Because computers intrinsically cannot deal with such knowledge, the upper boundary cannot be raised, even if the performance of computers improves substantially. The CPB, therefore, can utilize only a small portion of the knowledge and Condition 3 will not be met. As a result, it is practically impossible to construct an SPE that satisfies all three conditions.

Because only a small portion of the knowledge can be utilized by the CPB, wages are determined without this knowledge. As a result, rewards and/or punishments with regard to generating innovations will be uncertain for workers, and workers will not expect to be rewarded or punished for their efforts to innovate. That is, μ is far lower than unity ($\mu \approx 0$) and the incentive for workers to generate innovations (i.e., innovate to fix unexpected problems) is almost zero. The overall productivity Ω then becomes very low ($\Omega[0]$). Hence, by the AEPF, production in this modified SPE remains at a very low level.

5 SCIENTIFIC INNOVATIONS IN SPEs

Section 4 shows that workers will generate few innovations in SPEs as compared with DMEs, but is the same true for scientific and technical innovations (i.e., technology A in AEPF)? The USSR led the world in space and military technologies in the 1950s and 1960s, which suggests that an SPE may have some advantages in regard to scientific innovations. On the other hand, innovations in technologies for market-oriented goods and services in the USSR were unquestionably far behind those in DMEs at the same time.

As is the case with workers' innovations, Lange's model does not describe scientific innovations in an SPE because it is a static model, not a dynamic, let alone an endogenous growth, model. In static models, technology is assumed to be exogenously given, and thus with Lange's model, nothing certain can be said about the generation of scientific innovations in SPEs. An endogenous growth model is required to examine the technology generation mechanism in SPEs.

5.1 The model

Here, I use the endogenous growth model by Harashima (2010) to analyze scientific innovations in an SPE because this model has the notable property that it is free from the problems of scale effects and the influence of population growth (e.g., see Jones, 1995a,b; Aghion and Howitt, 1998; Peretto and Smulders, 2002).

5.1.1 The basic structure

Outputs Y_t are the sum of consumption C_t, the increase in capital input $\dot{K}_t$, and the increase in technology $\dot{A}_t$ such that

$$Y_t = C_t + \dot{K}_t + v\dot{A}_t \quad .$$

Thus,

$$\dot{k}_t = y_t - c_t - \frac{v\dot{A}_t}{L_t} - n_t k_t \quad ,$$

where $y_t = \frac{Y_t}{L_t}$, $k_t = \frac{K_t}{L_t}$, $c_t = \frac{C_t}{L_t}$, $n_t = \frac{\dot{L}_t}{L_t}$, L_t is labor input and $v(> 0)$ is a constant. A unit of K_t and v^{-1} of a unit of A_t are equivalent; that is, they are produced using the same quantities of inputs (capital, labor, and technology). This means that technologies are produced with capital, labor, and technology in the same way as consumer goods and services and capital. Unlike most idea-based growth models, no special mechanism is required for the production of technology because endogenous balanced growth (i.e., constant $k_t^{-1}A_t$) is not materialized by any special property of the production function of technology but by uncompensated knowledge spillovers and arbitrage between investments in capital and technology.

Because balanced growth paths are the focal point of this paper, Harrod-neutral technical progress is assumed. Hence, the production function is $Y_t = K_t^{1-\alpha}(A_t L_t)^{\alpha}$; thus,

$$y_t = A_t^{\alpha} k_t^{1-\alpha} \quad .$$

Population has an upper boundary and n_t = 0 after some future period; thus, $\lim_{t\to\infty} n_t = 0$ and $\lim_{t\to\infty} L_t = \overline{L}$, where $\overline{L}$ is a positive constant.

5.1.2 Substitution between investments in capital and technology

For any period,

$$m = L_t^{-1} M_t \quad , \tag{26}$$

where M_t is the number of firms (which are assumed to be identical) and m (> 0) is a constant. Equation (26) presents a natural assumption that the population and number of firms are positively correlated. In addition, for any period,

$$\frac{\partial Y_t}{\partial K_t} = \frac{\varpi}{M_t^{1-\rho}} \frac{\partial Y_t}{\partial (vA_t)} \quad ; \tag{27}$$

thus,

$$\frac{\partial y_t}{\partial k_t} = \frac{\varpi L_t^{\rho}}{m^{1-\rho} v} \frac{\partial y_t}{\partial A_t} \tag{28}$$

is always kept, where $\varpi(>1)$ and $\rho(0 \le \rho < 1)$ are constants. The parameter ρ describes the effect of uncompensated knowledge spillovers, and the parameter ϖ indicates the effect of patent protection. With patents, incomes are distributed not only to capital and labor but also to technology. For simplicity, the patent period is assumed to be indefinite, and no capital depreciation is assumed.

Equations (27) and (28) indicate that returns on investing in capital and technology for the investing firm are kept equal. The driving force behind the equations is that firms exploit all opportunities and select the most profitable investments at all times. Through arbitrage, this behavior leads to equal returns on investments in capital and technology. With substitution between investments in capital and technology, the model exhibits endogenous balanced growth. Because $\frac{\varpi}{mv}\frac{\partial y_t}{\partial A_t} = \frac{\partial y_t}{\partial k_t} \Leftrightarrow \frac{\varpi L_t^{\rho}\alpha}{m^{1-\rho}v} A_t^{\alpha-1} k_t^{1-\alpha} = (1-\alpha) A_t^{\alpha} k_t^{-\alpha}$, $A_t = \frac{\varpi L_t^{\rho}\alpha}{m^{1-\rho}v(1-\alpha)} k_t$ by equations (26) and (27) which lucidly indicates that $k_t^{-1}A_t$ = constant, and the model can therefore show balanced endogenous growth.

Equations (27) and (28) also indicate that the investing firm cannot obtain all the returns on its investment in technology. That is, although investment in technology increases Y_t, the investing firm's returns are only a fraction of the increase of Y_t, such that $\frac{\varpi}{M_t^{1-\rho}} \frac{\partial Y_t}{\partial (vA_t)}$, because knowledge spills over to other firms without compensation and other firms possess complementary technologies. Both MAR externalities (Marshall, 1890; Arrow, 1962; Romer, 1986) and Jacobs externalities (Jacobs, 1969) predict that uncompensated knowledge spillovers will increase as the number of firms increases, and scale effects have not actually been observed (Jones, 1995a), which implies that scale effects are almost canceled out by the effects of MAR and Jacobs externalities. Thus, the value of ρ is quite likely to be very small. From the point of view of a firm's behavior, a very small ρ appears to be quite natural. Because firms intrinsically seek profit opportunities, newly established firms work as hard as existing firms to profit from knowledge spillovers. Competition over technologies will increase as the number of firms increases. Through more fierce competition, uncompensated knowledge spillovers will also increase, eventually to the point that they increase at the same rate as the increase in the number of firms. The investing firm's fraction will thereby also be reduced at the same rate as the increase of the number of firms, which means that ρ will naturally decrease to zero as a result of firms' profit-seeking behavior.

Complementary technologies also reduce the fraction of $\frac{\partial Y_t}{\partial A_t}$ that the investing firm can obtain. If a new technology is effective only if it is combined with other technologies, the returns on investment in the new technology will belong not only to the investing firm but also to the firms that possess the other technologies. Because of both complementary technologies and uncompensated knowledge spillovers, the fraction of $\frac{\partial Y_t}{\partial A_t}$ that an investing firm can obtain on average will be very small; that is, ϖ will be far smaller than M_t except when M_t is very small.

5.1.3 The optimization

As a whole, the optimization problem of the representative household is to maximize the expected utility

$$E\int_0^\infty u(c_t)\exp(-\theta t)dt$$

subject to

$$\dot{k}_t = \frac{m^{1-\rho}L_t(1-\alpha)}{m^{1-\rho}L_t(1-\alpha)+\varpi L_t^\rho \alpha}\left[\left(\frac{\varpi L_t^\rho \alpha}{m^{1-\rho}v}\right)^\alpha (1-\alpha)^{-\alpha} k_t - c_t - n_t k_t\right] .$$

where $u(\bullet)$ is a constant relative risk aversion (CRRA) utility function and E is the expectation operator.

The optimal consumption growth rate is

$$\frac{\dot{c}_t}{c_t} = \varepsilon^{-1}\left[\left(\frac{\varpi\alpha}{mv}\right)^\alpha (1-\alpha)^{-\alpha} - \theta\right] ,$$

where $\varepsilon = -\frac{c_t u''}{u'}$ is the degree of relative risk aversion, which is constant. Transversality condition is satisfied if $-\lim_{t\to\infty}\frac{c_t}{k_t} < 0$.

5.2 Investments in technology in SPEs

In a DME, the income increase obtained by an investment in technology is distributed to the investing firm, although a part of the income increase leaks to other firms without compensation. The income increase provides incentives for entrepreneurs to invest in technology. Through competition and arbitrage in markets, investments in technology increase up to the point

$$\frac{\partial y_t}{\partial k_t} = \frac{\varpi}{m\nu}\frac{\partial y_t}{\partial A_t} \tag{29}$$

for $\rho = 0$.

If a CPB can make the same decisions on investments in technology for all of the dispersed production sites as those made by entrepreneurs in a DME, an SPE will be able to grow at the same rate as a DME. However, the same problem that arises for workers' innovations also arises for scientific innovations. Decisions about investing in technology require substantial intellectual activities; if anything, they represent one of the most difficult economic decisions and require careful consideration from various aspects because investments in technology are very risky and many of them will fail.

Broadly speaking, there are two types of risks in investments in technology: scientific risks and economic risks. Scientific risk is the risk that scientific innovations are not actually generated as intended. Economic risk is the risk that new products that are produced using the scientific innovations do not meet market demands. The scientific risk may be centrally managed by a CPB, but the economic risk will not be easily handled by a CPB. Taking an economic risk requires knowledge of the expected demand of the newly developed goods or services. Before deciding to invest in the new technology, the demand for the new goods or services in the particular time and place has to be forecasted by analyzing, evaluating, and guessing various factors utilizing the all related information, including knowledge of specific categories of goods and services in the particular time and place. Because the technology is new, information on the demand needs to be newly analyzed and evaluated using human intelligence. Without these intellectual activities, therefore, the degree of risk cannot be properly evaluated, and appropriate decisions on investment in technology are impossible. The necessity of using human intelligence indicates that the investment decisions in market-oriented technologies cannot be replaced by a simple rule. Hence, the CPB must obtain and adequately process the knowledge on the specific demands for all new goods and services. Clearly, similar to the case of workers' innovations, it is very difficult for the CPB to obtain all the knowledge that exists in all locations unless all managers correctly report the knowledge to the CPB.

5.3 Scientific innovations in SPEs

Section 5.2 indicates that the three conditions shown in Section 4 for workers' innovations in an SPE must also be satisfied for the CPB to sufficiently obtain and process the knowledge on the specific demands of all new goods and services. The amount of knowledge necessary for making decisions on investments in technology may be less than that for offering proper incentive for workers' innovations, but it will still be very difficult for the CPB to sufficiently process all of the knowledge obtained because analyzing and evaluating scientific and economic risks concerning innovations are intellectual activities. Therefore, the humans that conduct these activities intrinsically cannot be simply replaced with computers, and the CPB must process the results of millions or more managers' intellectual activities. In addition, technology investment decisions require risk taking. If the CPB lacks the mindset of risk-taking entrepreneurs, many relatively riskier but more productive investments in technology will be rejected.

If the CPB cannot correctly obtain and appropriately process the knowledge, far less relevant investments in technology will be made even though the return on investment in technology exceeds that in capital in actuality such that

$$\frac{\partial y_t}{\partial k_t} < \frac{\varpi}{mv} \frac{\partial y_t}{\partial A_t} \quad . \tag{30}$$

Inequality (30) indicates that, in an SPE, equation (29) can be replaced with

$$\frac{\partial y_t}{\partial k_t} = \kappa \frac{\varpi}{mv} \frac{\partial y_t}{\partial A_t} \quad ,$$

where κ is a constant and $0 < \kappa < 1$, and thereby the consumption growth rate on the balanced growth path is

$$\frac{\dot{c}_t}{c_t} = \varepsilon^{-1} \left[\left(\kappa \frac{\varpi \alpha}{mv} \right)^{\alpha} (1-\alpha)^{-\alpha} - \theta \right] \quad .$$

Clearly, an SPE grows at the lower rate than a DME.

That said, with regard to investments in technologies that are not market oriented (e.g., space or military technology), knowledge of demand is not needed because the primary aim of such investments is not to maximize economic outcomes. Even in a DME such investments are usually initiated by governments, not markets. Therefore, innovations in these fields may be similar in the two types of economies.

6 DISCUSSION

6.1 Are workers robot-like or intellectual human beings?

An essential difference between Lange's and Hayek's views lies in whether workers and managers are viewed as robot-like beings or intelligent beings with the capacity to innovate. In Lange's view, only the CPB needs to have intelligence. Workers and managers only implement simple non-intellectual tasks as ordered by the CPB because the CPB is considered to be a perfect all-knowing institution. Thereby, workers and managers require no intelligence or innovation. In fact, managers and workers should not generate innovations because the CPB's perfectly planned equilibrium would be destroyed by such actions. On the other hand, in Hayek's view, the CPB, workers, and managers are equally imperfect and know only a fraction of the universe.

Lange's view (or equivalently Walras' view) abstracts an important element of the DME and provides a very useful framework for analyzing the phenomenon of equilibrium. As long as the focus is only on the phenomenon of equilibrium, Lange's view is perfect. However, equilibrium is not the only area of interest in terms of economic activity. Lange lost the socialist calculation debate because his model did not account for a very important element of economy—workers and managers are all imperfect human beings who possess intelligence and generate a large number of innovations on a daily basis in dispersed production sites.

6.2 Partially decentralized SPEs

6.2.1 Partial decentralization

This paper concludes that a pure SPE is far less productive than a DME. However, if an SPE is partially decentralized, it may function almost as productively as a DME while maintaining the essential characteristics of an SPE. The first decentralization step is to delegate the power to determine wages and other aspects of personnel management to managers in the dispersed production sites. With this delegation, managers no longer need to report knowledge to the CPB, and thereby, conditions 2 and 3 no longer must be satisfied. The extra income gained by workers' innovations can be distributed by managers, and if the managers properly distribute the extra income, the incentive for workers to generate innovation will be sufficiently raised.

However, a problem arises with this modification. Managers must also have the incentive to properly distribute the extra income. One solution is that higher ranking managers evaluate the performances of lower ranking managers and determine their wages and other personnel management based on their performances. Eventually, most of wage settings and other aspects of personnel management need to be decentralized and the CPB, as the top of the hierarchy, only manages the next highest ranking personnel. Nevertheless, if capital incomes are still owned socially and the highest levels of economic decision making are made by the CPB, this partially decentralized economy may still be regarded as a type of SPE.

6.2.2 China's socialist market economy

Historically, pure SPEs have been rare. Mao's China, Cambodia under the Khmer Rouge, and North Korea are examples of almost pure SPEs. The USSR and other Soviet-bloc countries were partially decentralized, as was communist Yugoslavia. The current most substantially decentralized SPE is China.

Since the 1980s, China has gradually but substantially decentralized its economy. Lower level decision making has been mostly decentralized. However, most large companies are still owned by the state, provinces, or state-owned parent enterprises, so most capital is still socially owned. In addition, top-ranking managers in large companies are designated by the state and the highest levels of economic decision making are still made by the Communist Party. Therefore, although China's economy is largely decentralized, it can be regarded still as a type of SPE. China calls its economic system a "socialist market economy." Because decision making is largely decentralized, more workers' innovations should be generated than were generated in its earlier purer SPE. In fact, recent high growth rates in China may be partially driven by the increased number of workers' innovations. The number of scientific innovations may also have increased. Furthermore, because trade between China and other DMEs has substantially increased, China can now also import many technologies.

Nevertheless, because the highest levels of decision making are not decentralized, incentives to innovate may still be biased to some extent. Overall efficiency depends on the abilities and principles of the top-ranking officials in the Communist Party. If people in the top of the hierarchy are competent and are not corrupt, such a socialist market economy could work well in theory; but if they are incompetent or corrupt, the economy may be severely distorted. Particularly, corruption can be a significant issue in undemocratic countries such as China. As a result of corruption, non-negligible inefficiencies will remain in the system, and China's socialist market economy therefore may stay far less productive than other DMEs even though it is substantially decentralized.

China's economy has enjoyed high growth rates since the 1980s, but high growth does not necessarily indicate superiority of China's socialist market economy over other DMEs. Three special factors are worth noting in the current case of China. First, the high growth reflects the transition from the very unproductive Mao-era communist economy to a relatively more productive socialist market economy. Second, high growth rates are historically common during the early stages of capital accumulation in many economies, for example, in the USSR, Japan, and some other Asian countries. Third, opening up international trade will also initially accelerate the growth rate. Clearly, these factors are not limited to China's socialist market economy and do not indicate superiority. When China's transitional period is complete, the period of high growth in China will also most likely end, even if its productivity still remains lower than that in other DMEs. It is noteworthy that the share of consumption in GDP has been remarkably lower and capital has accumulated more rapidly and probably more inefficiently in China than in most DMEs. These phenomena imply that the Chinese economy still possesses some of the characteristics of old SPEs (e.g., the USSR); that is, its growth is largely driven by compulsory savings and capital accumulation engineered implicitly by the state (e.g., various regulations in factor markets may be substantially distorting the economy).

The economy of the USSR stagnated after the 1960s even though its rate of productivity was still far lower than that in other DMEs. My arguments indicate that an important reason for the stagnation and low productivity was that its economy was not sufficiently decentralized. Because of centralization, fewer workers' and scientific innovations were generated. China's current economy is far more decentralized than that of the USSR in the 1970s. Therefore, even after China's period of high growth ends, it may not immediately stagnate. In addition, unlike the USSR, China is more open to the world economy and is a member of the World Trade Organization. Hence, China can benefit from global technological progress and may continue to grow steadily at the same rate as the global technology growth rate.

7 CONCLUDING REMARKS

Because most socialist economies collapsed or changed dramatically to become considerably decentralized in the late twentieth century, the debate on the superiority between SPEs and DMEs has almost disappeared. However, a consensus has not necessarily been reached over the theoretical and practical reasons why SPEs failed. Currently, Hayek is considered to be the winner of the socialist calculation debate, but his arguments are prone to be misunderstood because his view goes beyond the Walrasian framework and his papers are descriptive and do not use mathematical models. This paper attempts to make Hayek's arguments more straightforward by using them as a basis to construct a model of total factor productivity.

The model is particularly based on Hayek's view on knowledge and focuses on innovations generated by ordinary workers. The model shows that productivity in an economy depends substantially on ordinary workers' innovations generated to fix unexpected problems through the use of their human intelligence. In a DME, workers' innovations (intelligence) are intrinsically utilized fully because they benefit both workers and entrepreneurs who pursue fully exploiting the opportunities that workers' innovations (intelligence) provide. On the other hand, they are not utilized in SPEs unless the knowledge of unexpected problems and workers' innovations (intelligence) is both adequately obtained and processed by the CPB, which was shown to be an impossible task. Hence, the model indicates that SPEs are intrinsically far less productive than DMEs. DMEs are similarly more productive with market-oriented scientific innovations, although not necessarily more productive with nonmarket goods and services (e.g., military technology).

An essential difference between Lange's and Hayek's views lies in whether workers and managers are viewed as robot-like beings or intelligent beings with the capacity to innovate. Lange lost the socialist calculation debate because his model did not account for a very important element of economy—workers and managers are all imperfect human beings who possess intelligence and generate a large number of innovations on a daily basis in dispersed production sites.

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Figure 1 ***The distribution of innovation***