＜論　　説＞

The Trade-off Relationship between Technological Performances

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【Introduction】

This article explains the trade-off relationship between technological performances in research and development（R&D）process. All technologies and products exhibit different technological performances. Generally, technological quality and price advantage have a trade-off relationship because costs increase with increasing quality. Other technological performances also exhibited a trade-off relationship.

For example, for an automobile, technological performance encompasses power, speed, acceleration, fuel efficiency, design, price advantage, credibility, strength, and safety（See *Note -1*）. Typically, high speeds and accelerations reduce safety and fuel efficiency. Similarly, vehicular strength reduces fuel efficiency（improves security）.

Another example is the case of a lens, where the set of technological performances includes the degree of transparency, refractive index, strength, light weight, and credibility[1]（See *Note -2*）.

For any product, the elements of technological performance can have a positive or negative relationship. A negative relationship implies a trade-off between the elements, which this article focuses on.

1. Nature of the Trade-off Relationship

In R&D processes, when a certain technological element improves performance, the performance of another is compromised. For example, when a product is lightened, its strength is usually sacrificed, and vice versa. In the immature stage, the performance of the two technological elements can be improved simultaneously to a certain point. However, as production approaches the mature stage, improving one technological element's performance must involve sacrificing that of the other element.

We hypothesize that, as the marginal rate of substitution increases, an extreme improvement in one element's performance essentially sacrifices that of the other.

Figure-1 shows the trade-off relationship between the performances of two technological elements（“a” and “b”）. Point “α” represents the immature stage, where both elements’ performances, “a” and “b,” can be simultaneously improved through R&D. After R&D efforts, we arrive at point “α^*”, representing the mature stage. In this stage, improving “a” ’s technological performance decreases “b” ’s performance, and vice versa.

Figure -1 shows an expanding curve moving in the upper- right direction that expresses the increasing marginal rate of substitution. Therefore, as the performance of one element improves, the performance of the other is increasingly jeopardized.

Breakthrough innovations must be realized to overcome this trade-off. Figure -2 demonstrates this breakthrough phenomenon. Passing from α_0^* to α_1^* and α_2^* requires technological breakthrough innovations. For example, new material innovation can simultaneously improve lighting and strengthen elements from previous limitations in the mature stage.

Meanwhile, β_0^1 and β_0^2 show the possible optional choice points of elemental technological performance levels of “a” and “b” within the limit of α_0^*. β_0^1 indicates comparatively higher（lower）level of performance of “a”（“b”）, while β_0^2 indicates relatively higher（lower）performance of “b”（“a”）. Similarly, β_1^1 or β_1^2 and β_2^1 or β_2^2 exhibit different combinations of elemental technological performances for “a” and “b” given the limitations α_1^* and α_2^*.

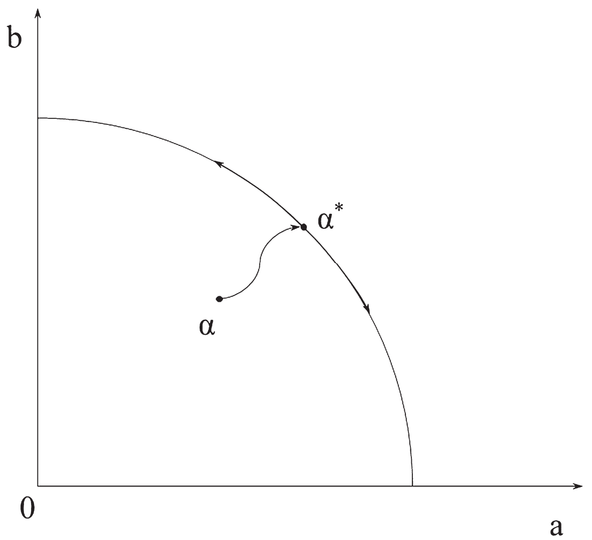

Figure -1.
Trade-off Relationship between the Technological Performances of “a” and “b”

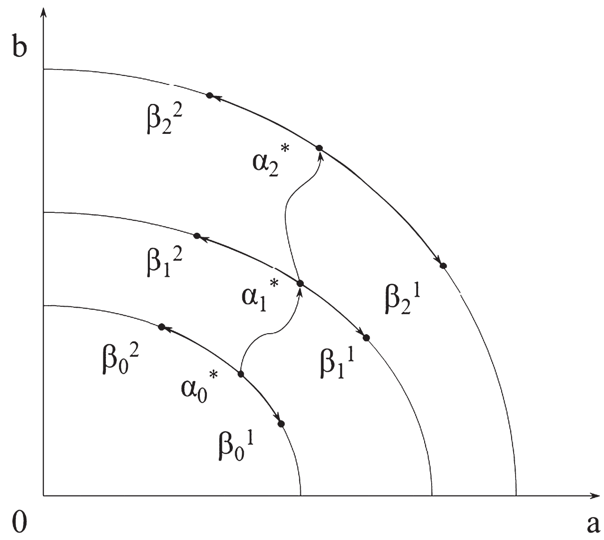

Figure -2
Technological Breakthrough Innovation Leaps the Trade-off Curve.

2. Concept of "Productive Standard"

Next, we hypothesize the "Productive Standard" concept, which refers to the necessary level of each technological element's performance for practical products. Figure -3 illustrates the trade-off relationship between the performances of technological elements "a" and "b," as well as the productive standard for each technological element.

The productive standard level of "a" requires higher quality than β_0^1, and "b" requires higher quality than β_0^2. Therefore, the technological performance level α_0^*cannot satisfy the productive standards of both "a" and "b". After technological innovation, α_1^*can realize the productive standards of both "a" and "b", both of which have optional selection points from β_1^1 to β_1^2.

Moreover, additional innovation reaches the point α_2^* while simultaneously realizing higher levels of performance for "a" and "b." Given this technological limitation, the "a" and "b" combination satisfies the productive standard extending from β_2^1 to β_2^2.

Figure -4 describes the trade-off relationship between the elemental technological performances "a" and "b," product standard level of each elemental technology, and technological S-curves.

S- curve I_a in the upper right side of Figure -4 describes the relationship between R&D efforts and the technological performance of "a." Cumulative R&D efforts concerned with "a" are described on the S- curve I_a, from A to C via B, they improve performance of the element "a" to "a_0". This subsequently helps improve the performance from "α" to "α_0^*". Similarly, S- curve I_b on the lower left side of Figure -4 implies that the cumulative R&D efforts for "b" help realize b_0, which

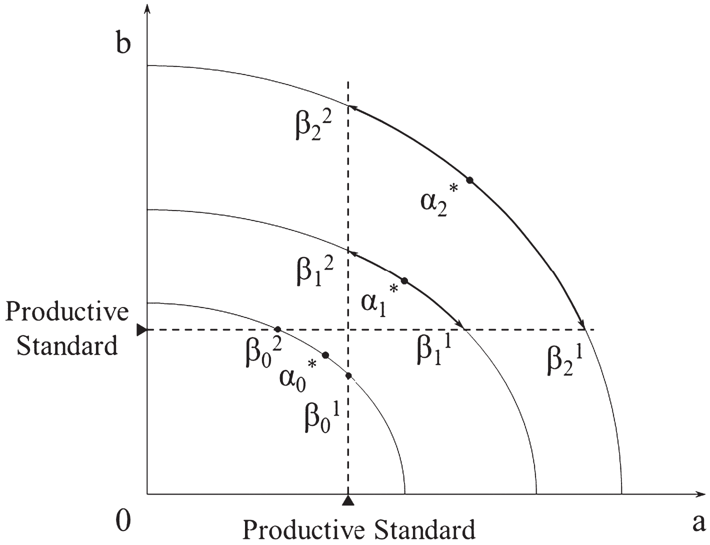

Figure -3
Productive Standard for each Technological Element

subsequently improves “α” to $α_0^*$.

However, the technological level of $α_0^*$ cannot satisfy the productive standard of both “a” and “b,”（which are described as P.S. $_a$ and P.S. $_b$ in the Figure -4). In the condition for $α_0^*$, a technological

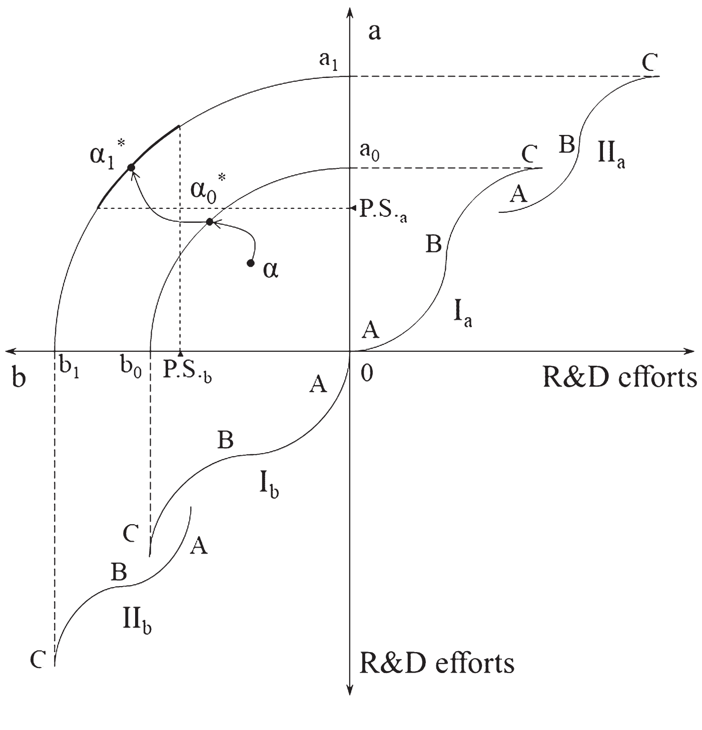

Figure -4
Trade-off Curves of Elemental Technological Performance and S- curves

breakthrough is inevitably required to satisfy the productive standard of both “a” and “b”.

The leap of the S- curve II_a in the upper right side of the Figure -4 indicates technological breakthrough innovation for “a,” which helps realize the jump from a_0 to a_1. Similarly, the leap of the S- curve II_b in the lower left side of the Figure -4 indicates technological breakthrough innovation for “b,” which helps realize the jump from “b_0” to “b_1.” These leaps of the S- curves help realize the jump from α_0^* to α_1^*. The condition α_1^* satisfies productive standards of both “a” and “b.”

The next section investigates the case of Bipolar R&D conducted by Hitachi Ltd. This technological innovation makes compatible the two trade-off technological elements of speed and energy efficiency.

3. Actual Case of Bipolar and Hi-Bipolar Development

In 1984, Hitachi Ltd. developed the bipolar complementary metal oxide semiconductor (BiCMOS) technology by combining the Bipolar and CMOS technologies. Figure -5 shows the trade-off relationship between the speed and energy efficiency of the Very Large-scale Integrated Circuit (VLSI).[2] (See *Note −3*)

Historically, VLSI technology was developed using CMOS and is characterized by low electric energy consumption. These are widely used as semiconductor elements in built-in electronic watches. However, large- scale computing requires high-speed semiconductor technology. Bipolar characteristics include high-speed and high electric energy consumption.

The increasing demand for high-quality electronic devices inevitably requires high-speed and economized electrical-energy consumption. Accordingly, the R&D Center of Hitachi Ltd. developed VLSI to ensure both high-speed and high electric-energy efficiency.[3]

They developed BiCMOS, which was compatible with high-speed and high electric-energy efficiency because it uses compound Bipolar and CMOS within the same fundamental circuit. BiCMOS innovation has been applied to various computing devices such as large, micro, and all-purpose computers.

According to cumulative R&D efforts, further innovation can shift the BiCMOS curve in Figure -5 to the upper right, where higher speed and lower energy consumption are compatible.

In 1986, the R&D Center of Hitachi Ltd. developed the high-performance Bipolar CMOS (Hi-BiCMOS), which has been applied to Static Random Access Memory (SRAM) and Hybrid Gate Array.[4] As illustrated in Figure -6, these innovations have doubled the speed of CMOS by maintaining its energy consumption at almost the same level as that of CMOS.

In Figure -6, E_C and S_C indicate the electrical energy efficiency and speed of the CMOS, respectively. S_B shows the Bipolar speed and $2S_C$ implies twice the speed of CMOS. The curve of

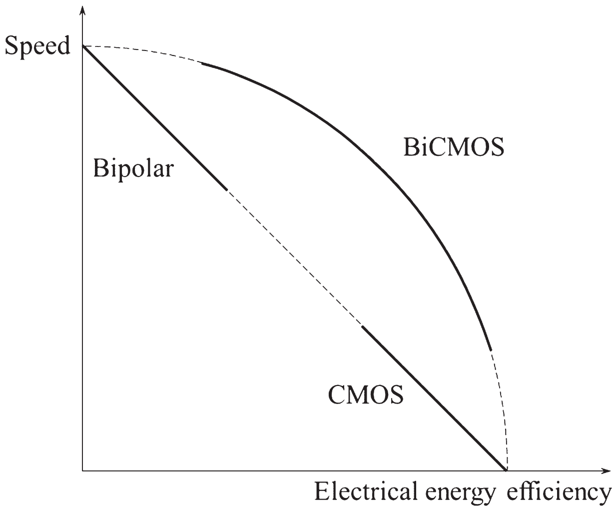

Figure -5
Trade-off between Speed and Energy Efficiency

Hi-BiCMOS illustrates that twice the speed of CMOS was realized with almost the same energy consumption as that of CMOS.

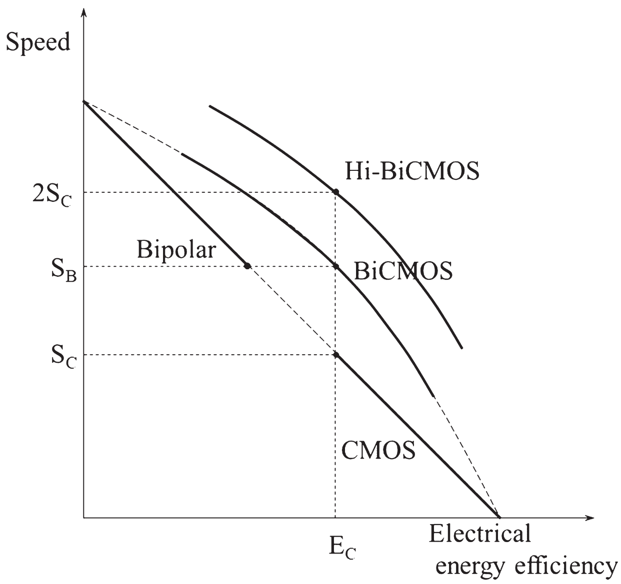

Figure -6
Breakthrough Innovation Shift-up the Trade-off Curve

4. Conclusion

This Article explained the trade-off relationship between the of product's technological performance elements. Multiple performance elements exhibited positive or negative relationships. This trade-off indicated negative relationship, such as weight reduction or enhanced strength. In the immature stages of technology, both elements could be improved through R&D. However, at the mature stage, a trade-off emerged.

Moreover, the marginal rate of substitution of the trade-off relationship was hypothesized to increase, because, according to the performance of one element increasing, the other element's performance must be increasingly sacrificed.

If the limit of the trade-off could not clear the productive standard, a practical product could not be realized, and technological breakthrough innovation was inevitable to overcome this limit. For every product, overcoming the trade-off limit was an unavoidable R&D process.

Furthermore, we investigated an actual case of R&D concerned with BiCMOS by the R&D Center of Hitachi Ltd.

Note –1

Generally, technological R&D theories do not consider cost performance or price advantages as elements of technological performance. Cost and price were discussed as incompatible and opposing factors to technological performance, because high costs and prices usually accompanied high quality.

However, this study includes cost and price advantages in technological performance because almost all of those advantages were fundamentally created by product or process innovation. For example, the computer-aided design/ computer-aided manufacturing (CAD/CAM) system is a typical electronic technological innovation that contributes to cost and price advantages. Therefore, cost and price elements can be included in technological performance.

Evidently, cost reduction due to material price declines in foreign exchange was not considered as a part of technological performance.

Note –2

HOYA Corporation investigated the different elements of lenses technological performance, such as trade-off relationship between producting-speeds and quality, and positive relationship between unit producing-speeds and mass production, from 1993 to 1995 through the Oyama Project linked to the Science and Technology Agency.

Note –3

This case study is based on interviews with researchers and engineers at the Super-High-Speed Processor Department of the R&D Center of Hitachi Ltd. The interviews were conducted in October 1993.

Bibliography

1）Oyama, K., “Behavioral Scientific Analysis of R&D Activity” *The Review of Economics and Commerce* Vol. 35 No.4. The Society of Economics, Kanagawa University 2000

2）Oyama, K.『技術革新の戦略と組織行動』第 5 章第 2 節　白桃書房 1999
Technological Innovation Strategy and Organizational Behavior, Chap.5 Section 2, Hakuto Press 1999

3）Torii, S. et al.「複合型ゲートアレイの開発」日立評論　66 巻 7 号　1984. 7
“Development of Hybrid Gate Array” Hitachi Hyoron Vol. 66 No.7 July 1984.

4）Masuda, I. et al.「Hi-BiCMOS 技術の展開」日立評論　68 巻 7 号　1986. 7
“Applications of HI-BiCMOS Technology” Hitachi Hyoron Vol. 68 No.7 July 1986.